Chapter 2
Principles Of Remote Sensing Systems

2-1 Introduction. The principles of remote sensing are based primarily on the properties of the electromagnetic spectrum and the geometry of airborne or satellite platforms relative to their targets. This chapter provides a background on the physics of remote sensing, including discussions of energy sources, electromagnetic spectra, atmospheric effects, interactions with the target or ground surface, spectral reflectance curves, and the geometry of image acquisition.

2-2 Definition of Remote Sensing.

a. Remote sensing describes the collection of data about an object, area, or phenomenon from a distance with a device that is not in contact with the object. More commonly, the term remote sensing refers to imagery and image information derived by both airborne and satellite platforms that house sensor equipment. The data collected by the sensors are in the form of electromagnetic energy (EM). Electromagnetic energy is the energy emitted, absorbed, or reflected by objects. Electromagnetic energy is synonymous to many terms, including electromagnetic radiation, radiant energy, energy, and radiation.

b. Sensors carried by platforms are engineered to detect variations of emitted and reflected electromagnetic radiation. A simple and familiar example of a platform carrying a sensor is a camera mounted on the underside of an airplane. The airplane may be a high or low altitude platform while the camera functions as a sensor collecting data from the ground. The data in this example are reflected electromagnetic energy commonly known as visible light. Likewise, spaceborne platforms known as satellites, such as Landsat Thematic Mapper (Landsat TM) or SPOT (Satellite Pour l'Observation de la Terra), carry a variety of sensors. Similar to the camera, these sensors collect emitted and reflected electromagnetic energy, and are capable of recording radiation from the visible and other portions of the spectrum. The type of platform and sensor employed will control the image area and the detail viewed in the image, and additionally they record characteristics of objects not seen by the human eye.

c. For this manual, remote sensing is defined as the acquisition, processing, and analysis of surface and near surface data collected by airborne and satellite systems.

2-3 Basic Components of Remote Sensing.

a. The overall process of remote sensing can be broken down into five components. These components are: 1) an energy source; 2) the interaction of this energy with particles in the atmosphere; 3) subsequent interaction with the ground target; 4) energy recorded by a sensor as data; and 5) data displayed digitally for visual and numerical interpretation. This chapter examines components 1–4 in detail. Component 5 will be discussed in Chapter 5. Figure 2-1 illustrates the basic elements of airborne and satellite remote sensing systems.

b. Primary components of remote sensing are as follows:

- Electromagnetic energy is emitted from a source.
- This energy interacts with particles in the atmosphere.
- Energy interacts with surface objects.
- Energy is detected and recorded by the sensor.
- Data are displayed digitally for visual and numerical interpretation on a computer.

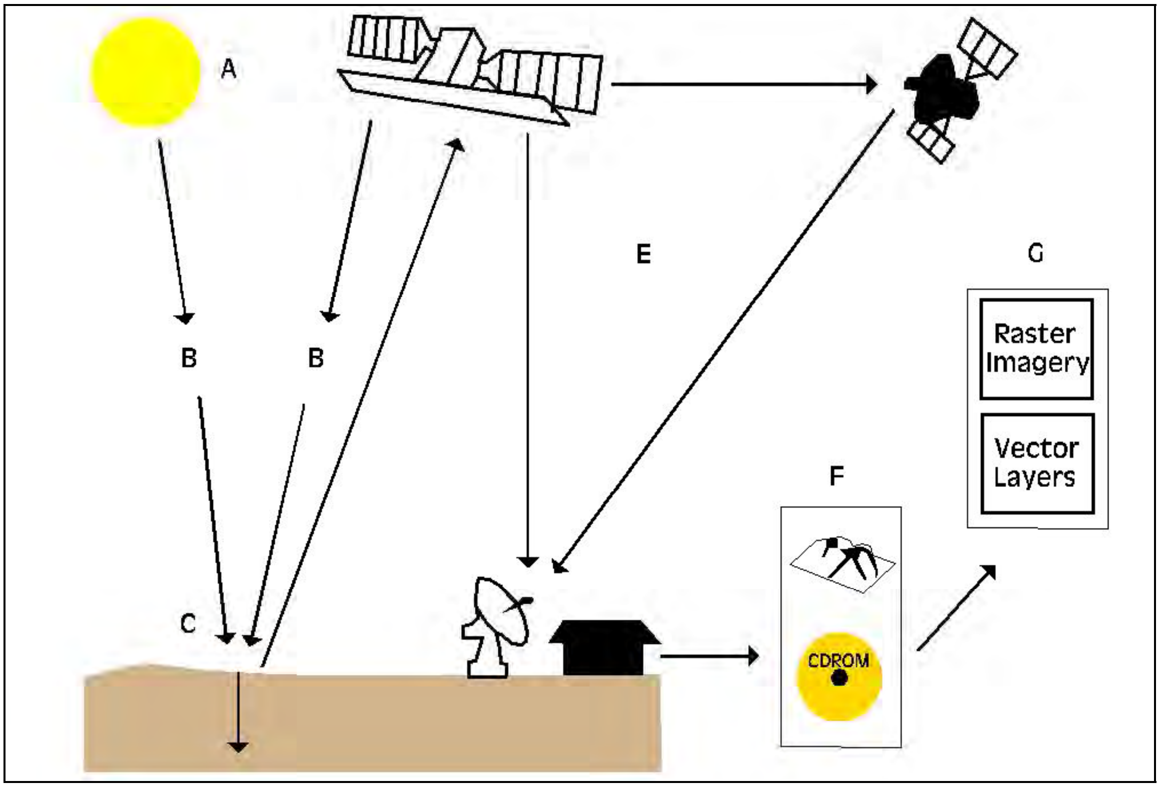


Figure 2-1. The satellite remote sensing process. **A—En**ergy source or illumination (electromagnetic energy); **B—r**adiation and the atmosphere; **C—interac**tion with the target; **D—re**cording of energy by the sensor; **E—**transmission, reception, and processing; **F—**interpretation and analysis; **G—ap**plication. Modified from http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter1/chapter1_1_e.html, courtesy of the Natural Resources Canada.

2-4 Component 1: Electromagnetic Energy Is Emitted From A Source.

a. Electromagnetic Energy: Source, Measurement, and Illumination. Remote sensing data become extremely useful when there is a clear understanding of the physical principles that govern what we are observing in the imagery. Many of these physical principles have been known and understood for decades, if not hundreds of years. For this manual, the discussion will be limited to the critical elements that contribute to our understanding of remote sensing principles. If you should need further explanation, there are numerous works that expand upon the topics presented below (see Appendix A).

b. Summary of Electromagnetic Energy. Electromagnetic energy or radiation is derived from the subatomic vibrations of matter and is measured in a quantity known as wavelength. The units of wavelength are traditionally given as micrometers (μm) or nanometers (nm). Electromagnetic energy travels through space at the speed of light and can be absorbed and reflected by objects. To understand electromagnetic energy, it is necessary to discuss the origin of radiation, which is related to the temperature of the matter from which it is emitted.

c. Temperature. The origin of all energy (electromagnetic energy or radiant energy) begins with the vibration of subatomic particles called photons (Figure 2-2). All objects at a temperature above absolute zero vibrate and therefore emit some form of electromagnetic energy. Temperature is a measurement of this vibrational energy emitted from an object. Humans are sensitive to the thermal aspects of temperature; the higher the temperature is the greater is the sensation of heat. A "hot" object emits relatively large amounts of energy. Conversely, a "cold" object emits relatively little energy.

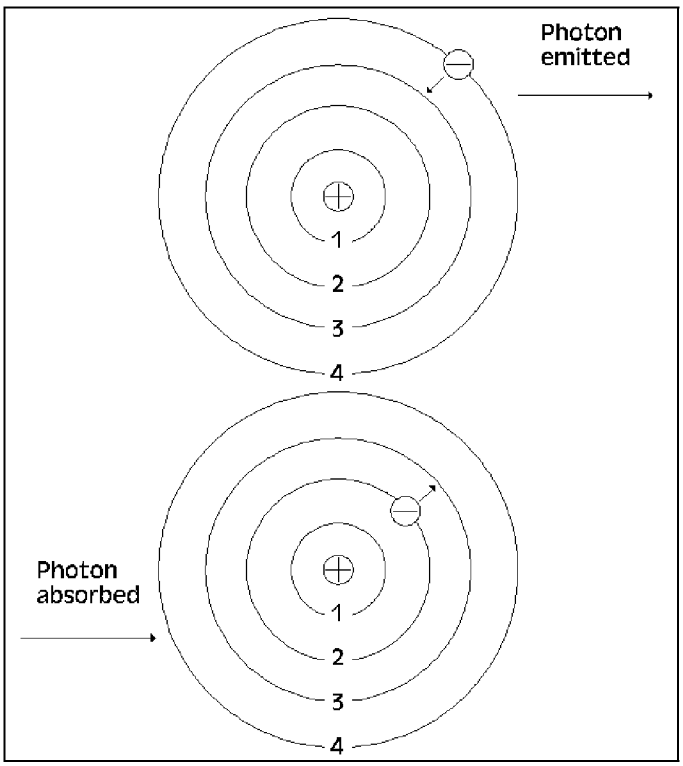


Figure 2-2. As an electron jumps from a higher to lower energy level, shown in top figure, a photon of energy is released. The absorption of photon energy by an atom allows electrons to jump from a lower to a higher energy state.

d. Absolute Temperature Scale. The lowest possible temperature has been shown to be –273.2°C and is the basis for the absolute temperature scale. The absolute temperature scale, known as Kelvin, is adjusted by assigning –273.2°C to 0 K ("zero Kelvin"; no degree sign). The Kelvin scale has the same temperature intervals as the Celsius scale, so conversion between the two scales is simply a matter of adding or subtracting 273 (Table 2-1). Because all objects with temperatures above, or higher than, zero Kelvin emit electromagnetic radiation, it is possible to collect, measure, and distinguish energy emitted from adjacent objects.

Table 2-1
Different scales used to measure object temperature. Conversion formulas are listed below.

Object	Fahrenheit (°F)	Celsius (°C)	Kelvin (K)
Absolute Zero	–459.7	–273.2	0.0
Frozen Water	32.0	0.0	273.16
Boiling Water	212.0	100.0	373.16
Sun	9981.0	5527.0	5800.0
Earth	46.4	8.0	281.0
Human body	98.6	37.0	310.0

Conversion Formulas:
Celsius to Fahrenheit: F° = (1.8 x C°) + 32
Fahrenheit to Celsius: C° = (F°- 32)/1.8
Celsius to Kelvin: K = C° + 273
Fahrenheit to Kelvin: K = [(F°- 32)/1.8] + 273

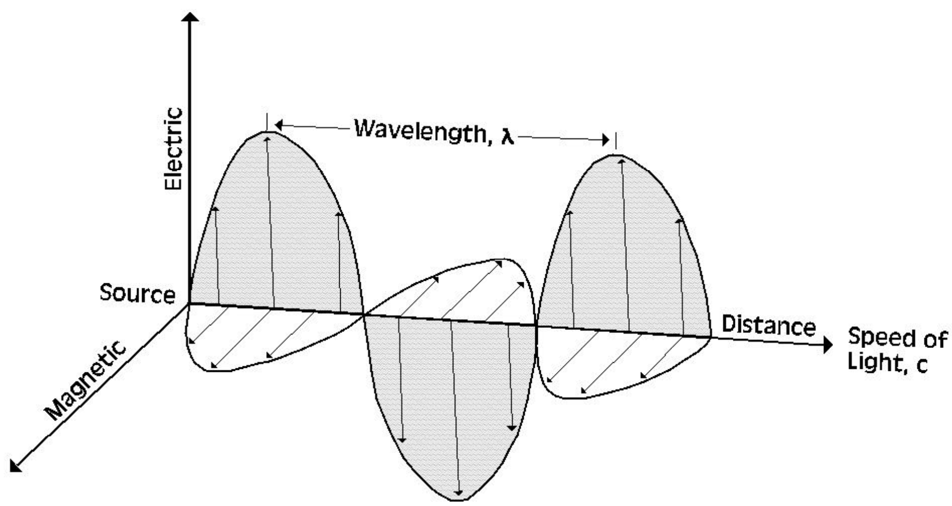


Figure 2-3. Propagation of the electromagnetic and magnetic field. Waves vibrate perpendicular to the direction of motion; electric and magnetic fields are at right angle to each other. These fields travel at the speed of light.

e. Nature of Electromagnetic Waves. Electromagnetic energy travels along the path of a sinusoidal wave (Figure 2-3). This wave of energy moves at the speed of light (3.00×10^8 m/s). All emitted and reflected energy travels at this rate, including light. Electromagnetic energy has two components, the electric and magnetic fields. This energy is defined by its wavelength (λ) and frequency (ν); see below for units. These fields are in-phase, perpendicular to one another, and oscillate normal to their direction of propagation (Figure 2-3). Familiar forms of radiant energy include X-rays, ultraviolet rays, visible light, microwaves, and radio waves. All of these waves move and behave similarly; they differ only in radiation intensity.

f. Measurement of Electromagnetic Wave Radiation.

(1) *Wavelength*. Electromagnetic waves are measured from wave crest to wave crest or conversely from trough to trough. This distance is known as wavelength (λ or "lambda"), and is expressed in units of micrometers (μm) or nanometers (nm) (Figures 2-4 and 2-5).

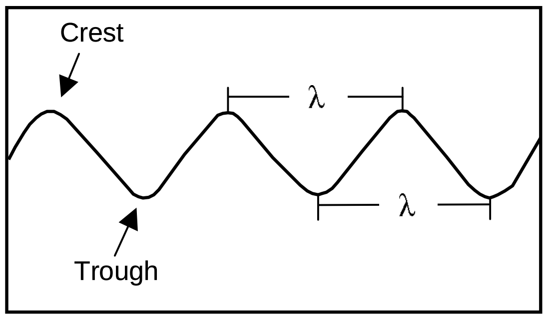


Figure 2-4. Wave morphology—wave-length (λ) is measured from crest-to-crest or trough-to-trough.

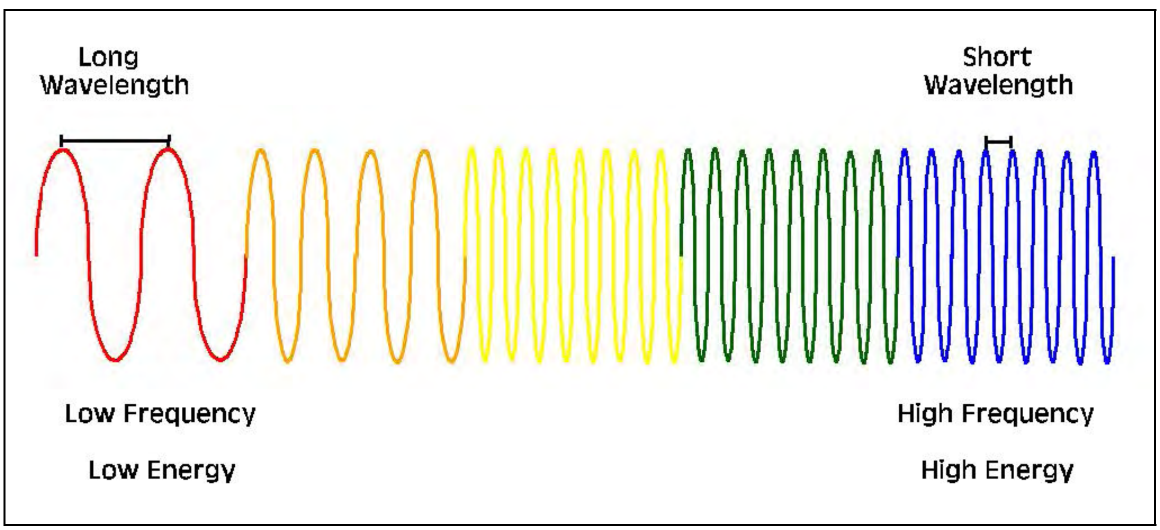


Figure 2-5. Long wavelengths maintain a low frequency and lower energy state relative to the short wavelengths.

(2) *Frequency*. The rate at which a wave passes a fixed point is known as the wave frequency and is denoted as ν ("nu"). The units of measurement for frequency are given as Hertz (Hz), the number of wave cycles per second (Figures 2-5 and 2-6).

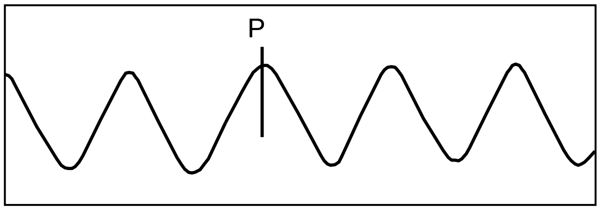


Figure 2-6. Frequency (ν) refers to the number of crests of waves of the same wavelength that pass by a point (P) in each second.

(3) *Speed of electromagnetic radiation (or speed of light).* Wavelength and frequency are inversely related to one another, in other words as one increases the other decreases. Their relationship is expressed as:

$$c = \lambda\nu \qquad (2\text{-}1)$$

where

c = 3.00×10^8 m/s, the speed of light
λ = the wavelength (m)
ν = frequency (cycles/second, Hz).

This mathematical expression also indicates that wavelength (λ) and frequency (ν) are both proportional to the speed of light (c). Because the speed of light (c) is constant, radiation with a small wavelength will have a high frequency; conversely, radiation with a large wavelength will have a low frequency.

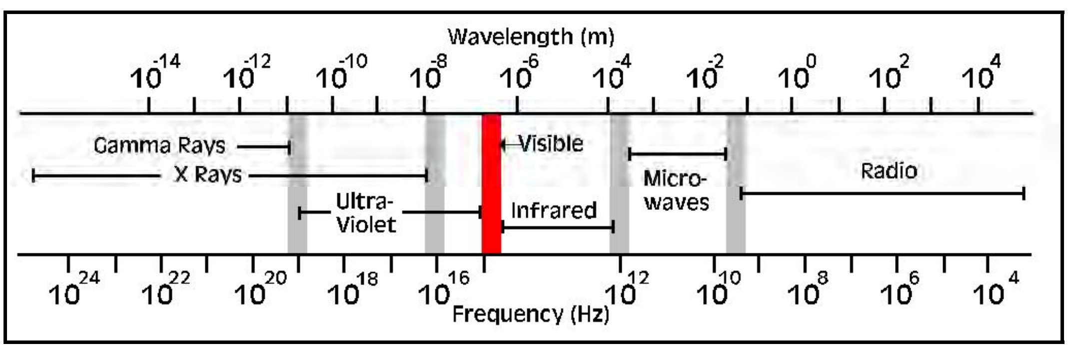


Figure 2-7. Electromagnetic spectrum displayed in meter and Hz units. Short wavelengths are shown on the left, long wavelength on the right. The visible spectrum shown in red.

g. Electromagnetic Spectrum. Electromagnetic radiation wavelengths are plotted on a logarithmic scale known as the electromagnetic spectrum. The plot typically increases in increments of powers of 10 (Figure 2-7). For convenience, regions of the electromagnetic spectrum are categorized based for the most part on methods of sensing their wavelengths. For example, the visible light range is a category spanning 0.4–0.7 µm. The minimum and maximum of this category is based on the ability of the human eye to sense radiation energy within the 0.4- to 0.7-µm wavelength range.

(1) Though the spectrum is divided up for convenience, it is truly a continuum of increasing wavelengths with no inherent differences among the radiations of varying wavelengths. For instance, the scale in Figure 2-8 shows the color blue to be approximately in the range of 435 to 520 nm (on other scales it is divided out at 446 to 520 nm). As the wavelengths proceed in the direction of green they become increasingly less blue and more green; the boundary is somewhat arbitrarily fixed at 520 nm to indicate this gradual change from blue to green.

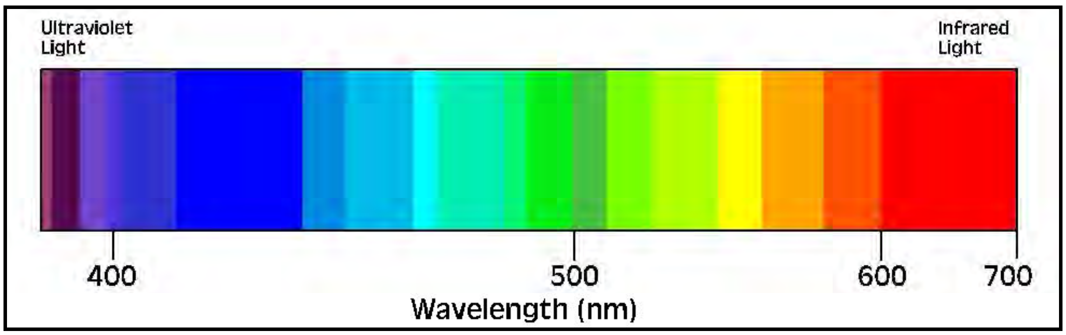


Figure 2-8. Visible spectrum illustrated here in color.

(2) Be aware of differences in the manner in which spectrum scales are drawn. Some authors place the long wavelengths to the right (such as those shown in this manual), while others place the longer wavelengths to the left. The scale can also be drawn on a vertical axis (Figure 2-9). Units can be depicted in meters, nanometers, micrometers, or a combination of these units. For clarity some authors add color in the visible spectrum to correspond to the appropriate wavelength.

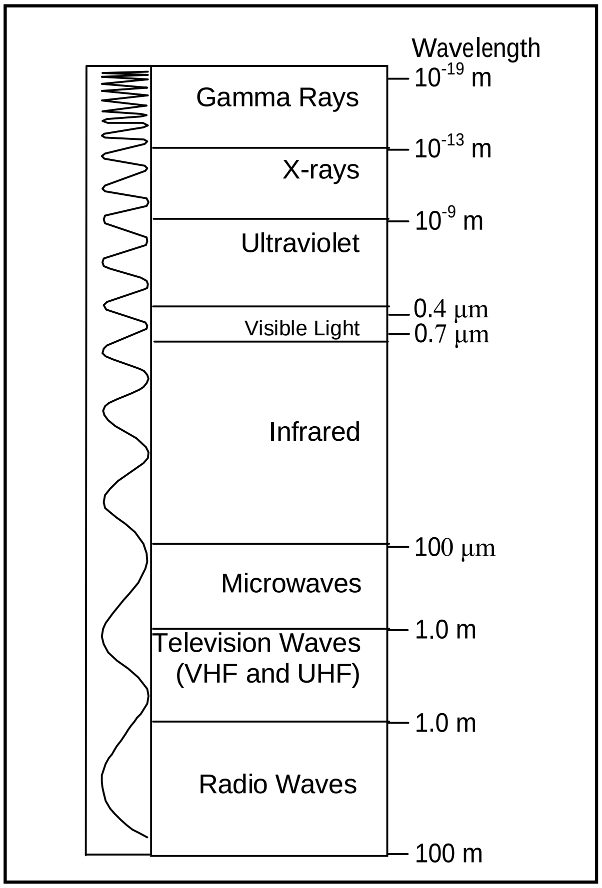


Figure 2-9. Electromagnetic spectrum on a vertical scale.

h. Regions of the Electromagnetic Spectrum. Different regions of the electromagnetic spectrum can provide discrete information about an object. The categories of the electromagnetic spectrum represent groups of measured electromagnetic radiation with similar wavelength and frequency. Remote sensors are engineered to detect specific spectrum wavelength and frequency ranges. Most sensors operate in the visible, infrared, and microwave regions of the spectrum. The following paragraphs discuss the electromagnetic spectrum regions and their general characteristics and potential use (also see Appendix B). The spectrum regions are discussed in order of increasing wavelength and decreasing frequency.

(1) *Ultraviolet*. The ultraviolet (UV) portion of the spectrum contains radiation just beyond the violet portion of the visible wavelengths. Radiation in this range has short wavelengths (0.300 to 0.446 µm) and high frequency. UV wavelengths are used in geologic and atmospheric science applications. Materials, such as rocks and minerals, fluoresce or emit visible light in the presence of UV radiation. The florescence associated with natural hydrocarbon seeps is useful in monitoring oil fields at sea. In the upper at-

mosphere, ultraviolet light is greatly absorbed by ozone (O_3) and becomes an important tool in tracking changes in the ozone layer.

(2) *Visible Light*. The radiation detected by human eyes is in the spectrum range aptly named the visible spectrum. Visible radiation or light is the only portion of the spectrum that can be perceived as colors. These wavelengths span a very short portion of the spectrum, ranging from approximately 0.4 to 0.7 µm. Because of this short range, the visible portion of the spectrum is plotted on a linear scale (Figure 2-8). This linear scale allows the individual colors in the visible spectrum to be discretely depicted. The shortest visible wavelength is violet and the longest is red.

(*a*) The visible colors and their corresponding wavelengths are listed below (Table 2-2) in micrometers and shown in nanometers in Figure 2.8.

Table 2-2
Wavelengths of the primary colors of the visible spectrum

Color	Wavelength
Violet	0.4–0.446 µm
Blue	0.446–0.500 µm
Green	0.500–0.578 µm
Yellow	0.578–0.592 µm
Orange	0.592–0.620 µm
Red	0.620–0.7 µm

(*b*) Visible light detected by sensors depends greatly on the surface reflection characteristics of objects. Urban feature identification, soil/vegetation discrimination, ocean productivity, cloud cover, precipitation, snow, and ice cover are only a few examples of current applications that use the visible range of the electromagnetic spectrum.

(3) *Infrared*. The portion of the spectrum adjacent to the visible range is the infrared (IR) region. The infrared region, plotted logarithmically, ranges from approximately 0.7 to 100 µm, which is more than 100 times as wide as the visible portion. The infrared region is divided into two categories, the reflected IR and the emitted or thermal IR; this division is based on their radiation properties.

(*a*) *Reflected Infrared*. The reflected IR spans the 0.7- to 3.0-µm wavelengths. Reflected IR shares radiation properties exhibited by the visible portion and is thus used for similar purposes. Reflected IR is valuable for delineating healthy verses unhealthy or fallow vegetation, and for distinguishing among vegetation, soil, and rocks.

(*b*) *Thermal Infrared*. The thermal IR region represents the radiation that is emitted from the Earth's surface in the form of thermal energy. Thermal IR spans the 3.0- to 100-µm range. These wavelengths are useful for monitoring temperature variations in land, water, and ice.

(4) *Microwave*. Beyond the infrared is the microwave region, ranging on the spectrum from 1 µm to 1 m (bands are listed in Table 2-3). Microwave radiation is the longest

wavelength used for remote sensing. This region includes a broad range of wavelengths; on the short wavelength end of the range, microwaves exhibit properties similar to the thermal IR radiation, whereas the longer wavelengths maintain properties similar to those used for radio broadcasts.

Table 2-3
Wavelengths of various bands in the microwave range

Band	Frequency (MHz)	Wavelength (cm)
Ka	40,000–26,000	0.8–1.1
K	26,500–18,500	1.1–1.7
X	12,500–8000	2.4–3.8
C	8000–4000	3.8–7.5
L	2000–1000	15.0–30.0
P	1000–300	30.0–100.0

(*a*) Microwave remote sensing is used in the studies of meteorology, hydrology, oceans, geology, agriculture, forestry, and ice, and for topographic mapping. Because microwave emission is influenced by moisture content, it is useful for mapping soil moisture, sea ice, currents, and surface winds. Other applications include snow wetness analysis, profile measurements of atmospheric ozone and water vapor, and detection of oil slicks.

(*b*) For more information on spectrum regions, see Appendix B.

i. Energy as it Relates to Wavelength, Frequency, and Temperature. As stated above, energy can be quantified by its wavelength and frequency. It is also useful to measure the intensity exhibited by electromagnetic energy. Intensity can be described by *Q* and is measured in units of Joules.

(1) *Quantifying Energy*. The energy released from a radiating body in the form of a vibrating photon traveling at the speed of light can be quantified by relating the energy's wavelength with its frequency. The following equation shows the relationship between wavelength, frequency, and amount of energy in units of Joules:

$$Q = h\,\nu \qquad (2\text{-}2)$$

Because $c = \lambda\nu$, *Q* also equals

$$Q = h\,c/\lambda$$

where

Q = energy of a photon in Joules (J)
h = Planck's constant (6.6×10^{-34} J s)
c = 3.00×10^{8} m/s, the speed of light
λ = wavelength (m)
ν = frequency (cycles/second, Hz).

The equation for energy indicates that, for long wavelengths, the amount of energy will be low, and for short wavelengths, the amount of energy will be high. For instance, blue light is on the short wavelength end of the visible spectrum (0.446 to 0.050 μm) while red is on the longer end of this range (0.620 to 0.700 μm). Blue light is a higher energy radiation than red light. The following example illustrates this point:

Example: Using $Q = h\,c/\lambda$, which has more energy blue or red light?

Solution: Solve for Q_{blue} (energy of blue light) and Q_{red} (energy of red light) and compare.

Calculation: λ_{blue}=0.425 μm, λ_{red}=0.660 μm (From Table 2-2)
$h = 6.6 \times 10^{-34}$ J s
$c = 3.00 \times 10^{8}$ m/s

* Don't forget to convert length μm to meters (not shown here)

Blue

$Q_{blue} = 6.6 \times 10^{-34}$ J s $(3.00\text{x}10^{8}$ m/s)/ 0.425 μm
$Q_{blue} = 4.66 \times 10^{-31}$ J

Red

$Q_{red} = 6.6 \times 10^{-34}$ J seconds $(3.00\text{x}10^{8}$ m/s)/ 0.660 μm
$Q_{red} = 3.00 \times 10^{-31}$ J

Answer: Because 4.66×10^{-31} J is greater than $3.00 \text{ x } 10^{-31}$ J *blue* has more energy.

This explains why the blue portion of a fire is hotter that the red portions.

(2) *Implications for Remote Sensing*. The relationship between energy and wavelengths has implications for remote sensing. For example, in order for a sensor to detect low energy microwaves (which have a large λ), it will have to remain fixed over a site for a relatively long period of time, know as dwell time. Dwell time is critical for the collection of an adequate amount of radiation. Conversely, low energy microwaves can be detected by "viewing" a larger area to obtain a detectable microwave signal. The latter is typically the solution for collecting lower energy microwaves.

j. Black Body Emission. Energy emitted from an object is a function of its surface temperature (refer to Paragraph 2-4*c* and *d*). An idealized object called a black body is used to model and approximate the electromagnetic energy emitted by an object. A black body completely absorbs and re-emits all radiation incident (striking) to its surface. A black body emits electromagnetic radiation at all wavelengths if its temperature is above 0 Kelvin. The Wien and Stefan-Boltzmann Laws explain the relationship between temperature, wavelength, frequency, and intensity of energy.

(1) *Wien's Displacement Law*. In Equation 2-2 wavelength is shown to be an inverse function of energy. It is also true that wavelength is inversely related to the temperature of the source. This is explained by Wein's displacement law (Equation 2-3):

$$L_m = A/T \tag{2-3}$$

where

L_m = maximum wavelength
A = 2898 μm Kelvin
T = temperature Kelvin emitted from the object.

Using this formula (Equation 2-3), we can determine the temperature of an object by measuring the wavelength of its incoming radiation.

Example: Using $L_m = A/T$, what is the maximum wavelength emitted by a human?

Solution: Solve for L_m given T from Table 2-1

Calculation: T = 98.6°C or 310 K (From Table 2-1)
A = 2898 μm Kelvin

L_m = 2898 μm K/310K

L_m =9.3 μm

Answer: Humans emit radiation at a maximum wavelength of 9.3 μm; this is well beyond what the eye is capable of seeing. Humans can see in the visible part of the electromagnetic spectrum at wavelengths of 0.4–0.7μm.

(2) *The Stefan-Boltzmann Law*. The Stefan-Boltzmann Law states that the total energy radiated by a black body per volume of time is proportional to the fourth power of temperature. This can be represented by the following equation:

$$M = \sigma T^4 \tag{2-4}$$

where

M = radiant surface energy in watts (w)
σ = Stefan-Boltzmann constant (5.6697×10^{-8} w/m^{2}K^4)
T = temperature in Kelvin emitted from the object.

This simply means that the total energy emitted from an object rapidly increases with only slight increases in temperature. Therefore, a hotter black body emits more radiation at each wavelength than a cooler one (Figure 2-10).

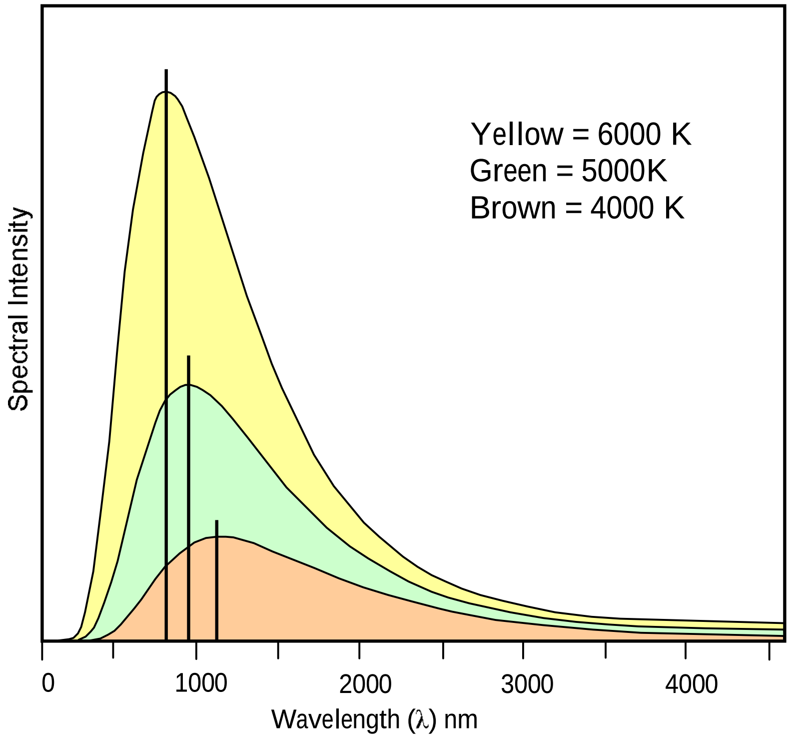


Figure 2-10. Spectral intensity of different emitted temperatures. The horizontal axis is wavelength in nm and the vertical axis is spectral intensity. The vertical bars denote the peak intensity for the temperatures presented. These peaks indicate a shift toward higher energies (lower wavelengths) with increasing temperatures. Modified from http://rst.gsfc.nasa.gov/Front/overview.html.

(3) *Summary*. Together, the Wien and Stefan-Boltzmann Laws are powerful tools. From these equations, temperature and radiant energy can be determined from an object's emitted radiation. For example, ocean water temperature distribution can be mapped by measuring the emitted radiation; discrete temperatures over a forest canopy can be detected; and surface temperatures of distant solar system objects can be estimated.

k. The Sun and Earth as Black Bodies. The Sun's surface temperature is 5800 K; at that temperature much of the energy is radiated as visible light (Figure 2-11). We can therefore see much of the spectra emitted from the sun. Scientists speculate the human eye has evolved to take advantage of the portion of the electromagnetic spectrum most readily available (i.e., sunlight). Also, note from the figure the Earth's emitted radiation peaks between 6 to 16 μm; to "see" these wavelengths one must use a remote sensing detector.

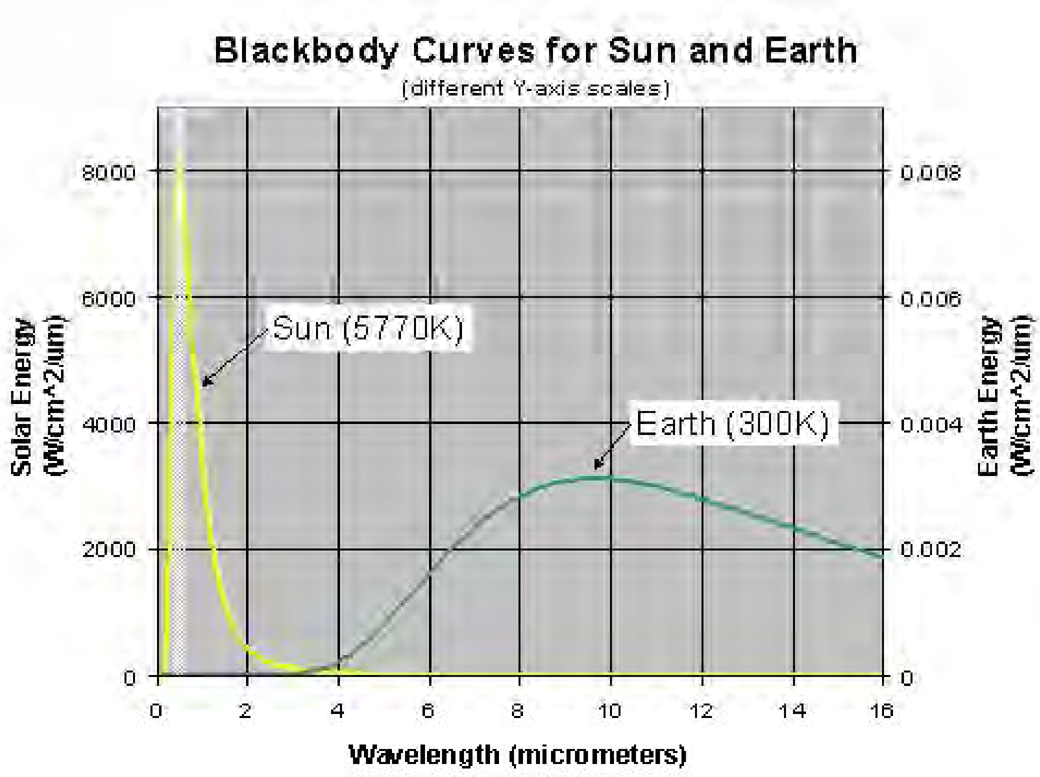


Figure 2-11. The Sun and Earth both emit electromagnetic radiation. The **Sun's** temperature is approximately 5770 Kelvin, the Ea**rth's** temperature is centered on 300 Kelvin.

l. Passive and Active Sources. The energy referred to above is classified as passive energy. Passive energy is emitted directly from a natural source. The Sun, rocks, ocean, and humans are all examples of passive sources. Remote sensing instruments are capable of collecting energy from both passive and active sources (Figure 2-1; path B). Active energy is energy generated and transmitted from the sensor itself. A familiar example of an active source is a camera with a flash. In this example visible light is emitted from a flash to illuminate an object. The reflected light from the object being photographed will return to the camera where it is recorded onto film. Similarly, active radar sensors transmit *their own* microwave energy to the surface terrain; the strength of energy returned to the sensor is recorded as representing the surface interaction. The Earth and Sun are the most common sources of energy used in remote sensing.

2-5 Component 2: Interaction of Electromagnetic Energy With Particles in the Atmosphere.

a. Atmospheric Effects. Remote sensing requires that electromagnetic radiation travel some distance through the Earth's atmosphere from the source to the sensor. Radiation from the Sun or an active sensor will initially travel through the atmosphere, strike the ground target, and pass through the atmosphere a second time before it reaches a sensor

(Figure 2-1; path B). The total distance the radiation travels in the atmosphere is called the path length. For electromagnetic radiation emitted from the Earth, the path length will be half the path length of the radiation from the sun or an active source.

(1) As radiation passes through the atmosphere, it is greatly affected by the atmospheric particles it encounters (Figure 2-12). This effect is known as atmospheric scattering and atmospheric absorption and leads to changes in intensity, direction, and wavelength size. The change the radiation experiences is a function of the atmospheric conditions, path length, composition of the particle, and the wavelength measurement relative to the diameter of the particle.

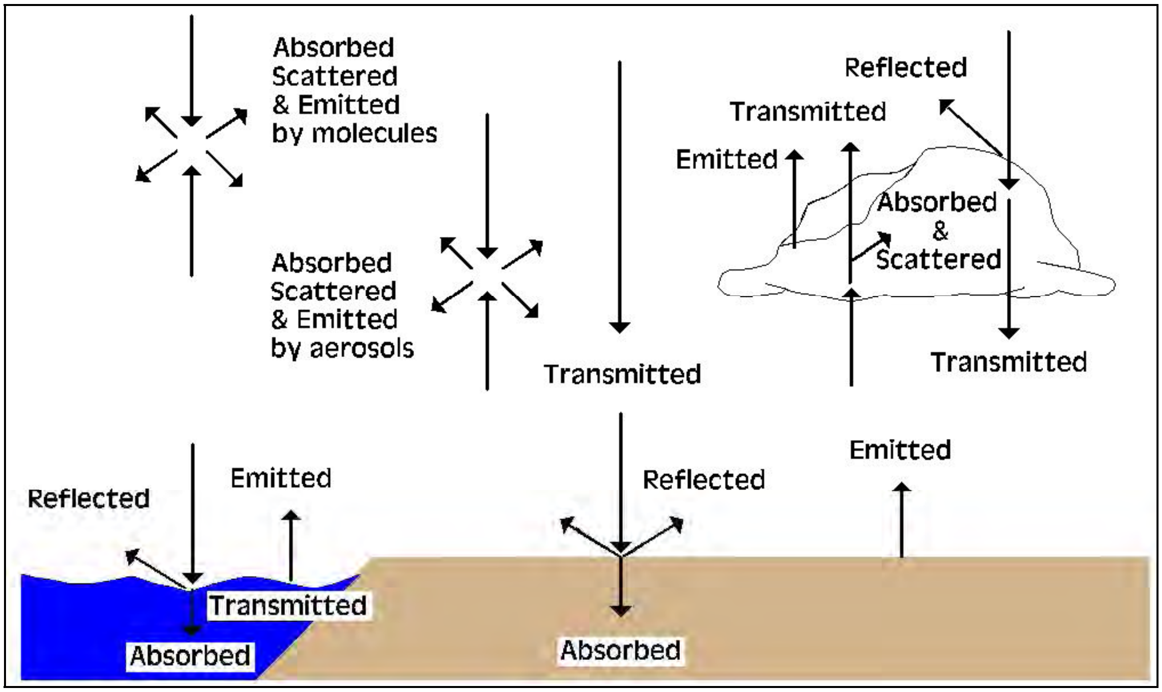


Figure 2-12. Various radiation obstacles and scatter paths. Modified from two sources, http://orbit-net.nesdis.noaa.gov/arad/fpdt/tutorial/12-atmra.gif and http://rst.gsfc.nasa.gov/Intro/Part2_4.html.

(2) Rayleigh scattering, Mie scattering, and nonselective scattering are three types of scatter that occur as radiation passes through the atmosphere (Figure 2-12). These types of scatter lead to the redirection and diffusion of the wavelength in addition to making the path of the radiation longer.

b. Rayleigh Scattering. Rayleigh scattering dominates when the diameter of atmospheric particles are much smaller than the incoming radiation wavelength ($\phi<\lambda$). This leads to a greater amount of short wavelength scatter owing to the small particle size of atmospheric gases. Scattering is inversely proportional to wavelength by the 4th power, or…

$$\text{Rayleigh Scatter} = 1/\lambda^4 \tag{2-5}$$

where λ is the wavelength (m). This means that short wavelengths will undergo a large amount of scatter, while large wavelengths will experience little scatter. Smaller wavelength radiation reaching the sensor will appear more diffuse.

c. Why the sky is blue? Rayleigh scattering accounts for the Earth's blue sky. We see predominately blue because the wavelengths in the blue region (0.446–0.500 μm) are more scattered than other spectra in the visible range. At dusk, when the sun is low in the horizon creating a longer path length, the sky appears more red and orange. The longer path length leads to an increase in Rayleigh scatter and results in the depletion of the blue wavelengths. Only the longer red and orange wavelengths will reach our eyes, hence beautiful orange and red sunsets. In contrast, our moon has no atmosphere; subsequently, there is no Rayleigh scatter. This explains why the moon's sky appears black (shadows on the moon are more black than shadows on the Earth for the same reason, see Figure 2-13).

Figure 2-13. Moon rising in the Earth's horizon (left). The Earth's atmosphere appears blue due to Rayleigh Scatter. Photo taken from the moon's surface shows the Earth rising (right). The Moon has no atmosphere, thus no atmospheric scatter. Its sky appears black. Images taken from: http://antwrp.gsfc.nasa.gov/apod/ap001028.html, and http://antwrp.gsfc.nasa.gov/apod/ap001231.html.

d. Mie Scattering. Mie scattering occurs when an atmospheric particle diameter is equal to the radiation's wavelength ($\phi = \lambda$). This leads to a greater amount of scatter in the long wavelength region of the spectrum. Mie scattering tends to occur in the presence of water vapor and dust and will dominate in overcast or humid conditions. This type of scattering explains the reddish hues of the sky following a forest fire or volcanic eruption.

e. Nonselective Scattering. Nonselective scattering dominates when the diameter of atmospheric particles (5–100 μm) is much larger than the incoming radiation wavelength ($\phi >> \lambda$). This leads to the scatter of visible, near infrared, and mid-infrared. All these wavelengths are equally scattered and will combine to create a white appearance in the sky; this is why clouds appear white (Figure 2-14).

Figure 2-14. Non-selective scattering by larger atmospheric particles (like water droplets) affects all wavelengths, causing white clouds.

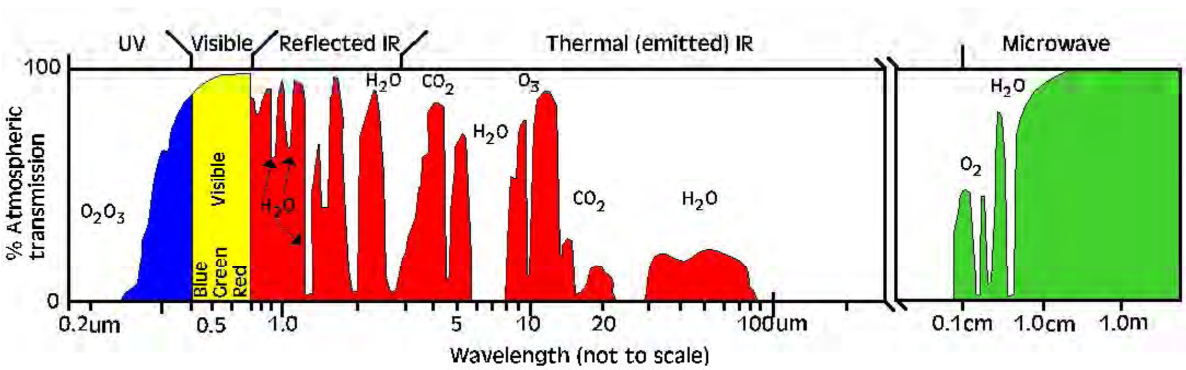


Figure 2-15. Atmospheric windows with wavelength on the x-axis and percent transmission measured in hertz on the y-axis. High transmission corresponds to an "atmospheric window," which allows radiation to penetrate the Earth's atmosphere. The chemical formula is given for the molecule responsible for sunlight absorption at particular wavelengths across the spectrum. Modified from http://earthobservatory.nasa.gov:81/Library/RemoteSensing/remote_04.html.

f. Atmospheric Absorption and Atmospheric Windows. Absorption of electromagnetic radiation is another mechanism at work in the atmosphere. This phenomenon occurs as molecules absorb radiant energy at various wavelengths (Figure 2-12). Ozone (O_3), carbon dioxide (CO_2), and water vapor (H_2O) are the three main atmospheric compounds that absorb radiation. Each gas absorbs radiation at a particular wavelength. To a lesser extent, oxygen (O_2) and nitrogen dioxide (NO_2) also absorb radiation (Figure 2-15). Below is a summary of these three major atmospheric constituents and their significance in remote sensing.

g. The role of atmospheric compounds in the atmosphere.

(1) *Ozone*. Ozone (O_3) absorbs harmful ultraviolet radiation from the sun. Without this protective layer in the atmosphere, our skin would burn when exposed to sunlight.

(2) *Carbon Dioxide*. Carbon dioxide (CO_2) is called a greenhouse gas because it greatly absorbs thermal infrared radiation. Carbon dioxide thus serves to trap heat in the atmosphere from radiation emitted from both the Sun and the Earth.

(3) *Water vapor*. Water vapor (H_2O) in the atmosphere absorbs incoming long-wave infrared and shortwave microwave radiation (22 to 1 μm). Water vapor in the lower atmosphere varies annually from location to location. For example, the air mass above a desert would have very little water vapor to absorb energy, while the tropics would have high concentrations of water vapor (i.e., high humidity).

(4) *Summary*. Because these molecules absorb radiation in very specific regions of the spectrum, the engineering and design of spectral sensors are developed to collect wavelength data not influenced by atmospheric absorption. The areas of the spectrum that are not severely influenced by atmospheric absorption are the most useful regions, and are called atmospheric windows.

h. Summary of Atmospheric Scattering and Absorption. Together atmospheric scatter and absorption place limitations on the spectra range useful for remote sensing. Table 2-4 summarizes the causes and effects of atmospheric scattering and absorption due to atmospheric effects.

i. Spectrum Bands. By comparing the characteristics of the radiation in atmospheric windows (Figure 2-15; areas where reflectance on the y-axis is high), groups or bands of wavelengths have been shown to effectively delineate objects at or near the Earth's surface. The visible portion of the spectrum coincides with an atmospheric window, and the maximum emitted energy from the Sun. Thermal infrared energy emitted by the Earth corresponds to an atmospheric window around 10 μm, while the large window at wavelengths larger than 1 mm is associated with the microwave region (Figure 2-16).

Table 2-4
Properties of Radiation Scatter and Absorption in the Atmosphere

Atmospheric Scattering	Diameter (ϕ) of particle relative to incoming wavelength (λ)	Result
Rayleigh scattering	$\phi<\lambda$	Short wavelengths are scattered
Mie scattering	$\phi=\lambda$	Long wavelengths are scattered
Nonselective scattering	$\phi>>\lambda$	All wavelengths are equally scattered
Absorption	No relationship	CO_2, H_20, and O_3 remove wavelengths

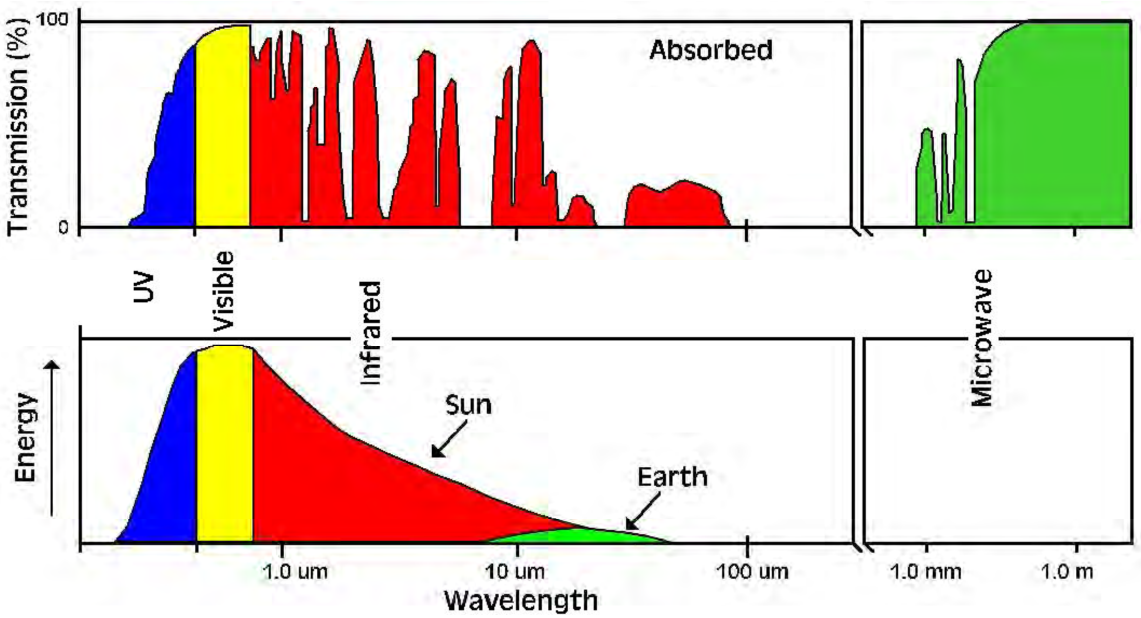


Figure 2-16. Atmospheric windows related to the emitted energy supplied by the sun and the Earth. Notice that the s**un's maximum output (sho**wn in yellow) coincides with an atmospheric window in the visible range of the spectrum. This phenomenon is important in optical remote sensing. Modified from http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter1/chapter1_4_e.html.

j. Geometric Effects. Random and non-random error occurs during the acquisition of radiation data. Error can be attributed to such causes as sun angle, angle of sensor, elevation of sensor, skew distortion from the Earth's rotation, and path length. Malfunctions in the sensor as it collects data and the motion of the platform are additional sources of error. As the sensor collects data, it can develop sweep irregularities that result in hundreds of meters of error. The pitch, roll, and yaw of platforms can create hundreds to thousands of meters of error, depending on the altitude and resolution of the sensor. Geometric corrections are typically applied by re-sampling an image, a process that shifts and recalculates the data. The most commonly used re-sampling techniques include the use of ground control points (see Chapter 5), applying a mathematical model, or re-sampling by nearest neighbor or cubic convolution.

k. Atmospheric and Geometric Corrections. Data correction is required for calculating reflectance values from radiance values (see Equation 2-5 below) recorded at a sensor and for reducing positional distortion caused by known sensor error. It is extremely important to make corrections when comparing one scene with another and when performing a temporal analysis. Corrected data can then be evaluated in relation to a spectral data library (see Paragraph 2-6*b*) to compare an object to its standard. Corrections are not necessary if objects are to be distinguished by relative comparisons within an individual scene.

l. Atmospheric Correction Techniques. Data can be corrected by re-sampling with the use of image processing software such as ERDAS Imagine or ENVI, or by the use of specialty software. In many of the image processing software packages, atmospheric correction models are included as a component of an import process. Also, data may have some corrections applied by the vendor. When acquiring data, it is important to be aware of any corrections that may have been applied to the data (see Chapter 4). Correction models can be mathematically or empirically derived.

m. Empirical Modeling Corrections. Measured or empirical data collected on the ground at the time the sensor passes overhead allows for a comparison between ground spectral reflectance measurements and sensor radiation reflectance measurements. Typical data collection includes spectral measurements of selected objects within a scene as well as a sampling of the atmospheric properties that prevailed during sensor acquisition. The empirical data are then compared with image data to interpolate an appropriate correction. Empirical corrections have many limitations, including cost, spectral equipment availability, site accessibility, and advanced preparation. It is critical to time the field spectral data collection to coincide with the same day and time the satellite collects radiation data. This requires knowledge of the satellite's path and revisit schedule. For archived data it is impossible to collect the field spectral measurements needed for developing an empirical model that will correct atmospheric error. In such a case, a mathematical model using an estimate of the field parameters must complete the correction.

n. Mathematical Modeling Corrections. Alternatively, corrections that are mathematically derived rely on estimated atmospheric parameters from the scene. These parameters include visibility, humidity, and the percent and type of aerosols present in the atmosphere. Data values or ratios are used to determine the atmospheric parameters. Subsequently a mathematical model is extracted and applied to the data for re-sampling. This type of modeling can be completed with the aid of software programs such as 6S, MODTRAN, and ATREM (see http://atol.ucsd.edu/~pflatau/rtelib/ for a list and description of correction modeling software).

2-6 Component 3: Electromagnetic Energy Interacts with Surface and Near Surface Objects.

a. Energy Interactions with the Earth's Surface. Electromagnetic energy that reaches a target will be absorbed, transmitted, and reflected. The proportion of each depends on the composition and texture of the target's surface. Figure 2-17 illustrates these three interactions. Much of remote sensing is concerned with reflected energy.

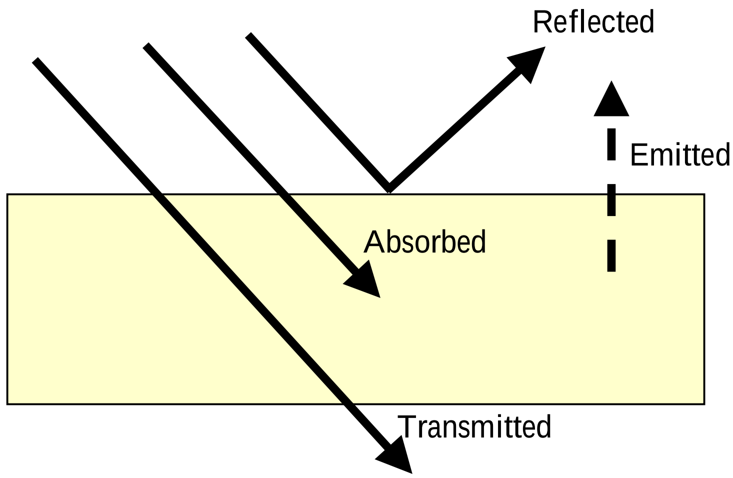


Figure 2-17. Radiation striking a target is reflected, absorbed, or transmitted through the medium. Radiation is also emitted from ground targets.

(1) *Absorption*. Absorption occurs when radiation penetrates a surface and is incorporated into the molecular structure of the object. All objects absorb incoming incident radiation to some degree. Absorbed radiation can later be emitted back to the atmosphere. Emitted radiation is useful in thermal studies, but will not be discussed in detail in this work (see Lillisand and Keifer [1994] *Remote Sensing and Image Interpretation* for information on emitted energy).

(2) *Transmission*. Transmission occurs when radiation passes through material and exits the other side of the object. Transmission plays a minor role in the energy's interaction with the target. This is attributable to the tendency for radiation to be absorbed before it is entirely transmitted. Transmission is a function of the properties of the object.

(3) *Reflection*. Reflection occurs when radiation is neither absorbed nor transmitted. The reflection of the energy depends on the properties of the object and surface roughness relative to the wavelength of the incident radiation. Differences in surface properties allow the distinction of one object from another.

(*a*) Absorption, transmission, and reflection are related to one another by

$$E_I = E_A + E_T + E_R \tag{2-6}$$

where

E_I = incident energy striking an object
E_A = absorbed radiation
E_T = transmitted energy
E_R = reflected energy.

(*b*) The amount of each interaction will be a function of the incoming wavelength, the composition of the material, and the smoothness of the surface.

(4) *Reflectance of Radiation*. Reflectance is simply a measurement of the percentage of incoming or incident energy that a surface reflects

$$\text{Reflectance} = \text{Reflected energy}/\text{Incident energy} \tag{2-7}$$

where incident energy is the amount of incoming radiant energy and reflected energy is the amount of energy bouncing off the object. Or from equation 2-5:

$$E_I = E_A + E_T + E_R$$

$$\text{Reflectance} = E_R/E_I \tag{2-8}$$

Reflectance is a fixed characteristic of an object. Surface features can be distinguished by comparing the reflectance of different objects at each wavelength. Reflectance comparisons rely on the unchanging proportion of reflected energy relative to the sum of incoming energy. This permits the distinction of objects regardless of the amount of incident energy. Unique objects reflect differently, while similar objects only reflect differently if there has been a physical or chemical change. Note: reflectance is not the same as reflection.

Specular and diffuse reflection

The nature of reflectance is controlled by the wavelength of the radiation relative to the surface texture. Surface texture is defined by the roughness or bumpiness of the surface relative to the wavelength. Objects display a range of reflectance from diffuse to specular. Specular reflectance is a mirror-like reflection, which occurs when an object with a smooth surface reflects in one direction. The incoming radiation will reflect off a surface at the same angle of incidence (Figure 2-18). Diffuse or Lambertian reflectance reflects in all directions owing to a rough surface. This type of reflectance gives the most information about an object.

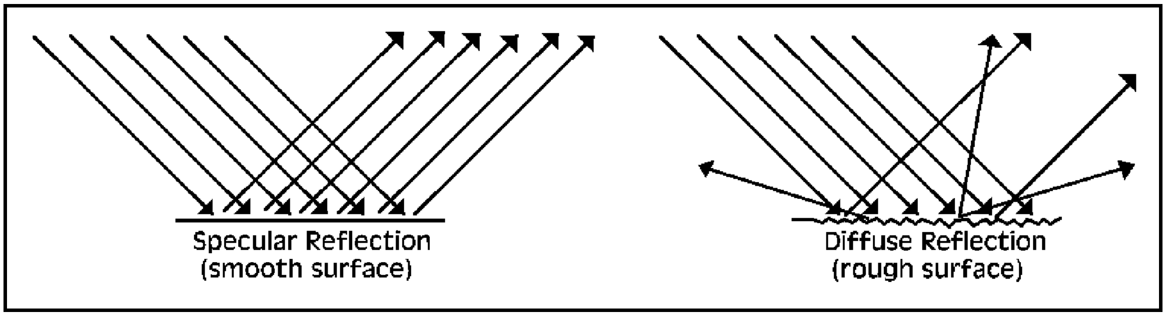


Figure 2-18. Specular reflection or mirror-like reflection (left) and diffuse reflection (right).

(5) *Spectral Radiance*. As reflected energy radiates away from an object, it moves in a hemi-spherical path. The sensor measures only a small portion of the reflected radiation—the portion along the path between the object and the sensor (Figure 2-19). This measured radiance is known as the spectral radiance (Equation 2-9).

$$I = \text{Reflected radiance} + \text{Emitted radiance} \qquad \text{2-9}$$

where I = radiant intensity in watts per steradian (W sr^{-1}). (Steradian is the unit of cone angle, abbreviated sr, 1 sr equals 4π. See the following for more details on steradian.) http://whatis.techtarget.com/definition/0%2C%2Csid9_gci528813%2C00.html

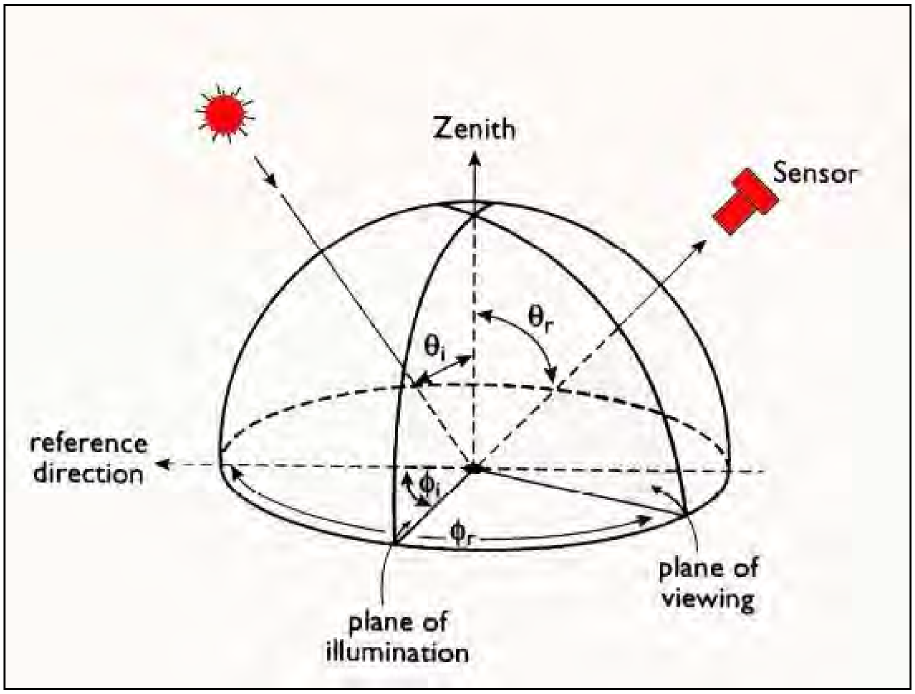


Figure 2-19. Diffuse reflection of radiation from a single target point. Radiation moves outward in a hemispherical path. Notice the sensor only samples radiation from a single vector. Modified after http://rst.gsfc.nasa.gov/Intro/Part2_3html.html.

(6) *Summary*. Spectral radiance is the amount of energy received at the sensor per time, per area, in the direction of the sensor (measured in steradian), and it is measured per wavelength. The sensor therefore measures the fraction of reflectance for a given area/time for every wavelength as well as the emitted. Reflected and emitted radiance is calculated by the integration of energy over the reflected hemisphere resulting from diffuse reflection (see http://rsd.gsfc.nasa.gov/goes/text/reflectance.pdf for details on this complex calculation). Reflected radiance is orders of magnitude greater than emitted radiance. The following paragraphs, therefore, focus on reflected radiance.

b. Spectral Reflectance Curves.

(1) *Background*.

(*a*) Remote sensing consists of making spectral measurements over space: how much of what "color" of light is coming from what place on the ground. One thing that a remote sensing applications scientist hopes for, but which is not always true, is that surface features of interest will have different colors so that they will be distinct in remote sensing data.

(*b*) A surface feature's color can be characterized by the *percentage* of incoming electromagnetic energy (illumination) it reflects at each wavelength across the electromagnetic spectrum. This is its spectral reflectance curve or "spectral signature"; it is an unchanging property of the material. For example, an object such as a leaf may reflect 3% of incoming blue light, 10% of green light and 3% of red light. The amount of light it reflects depends on the amount and wavelength of incoming illumination, but the percents are constant. Unfortunately, remote sensing instruments do not record reflectance directly, rather radiance, which is the *amount* (not the percent) of electromagnetic energy received in selected wavelength bands. A change in illumination, more or less intense sun for instance, will change the radiance. Spectral signatures are often represented as plots or graphs, with wavelength on the horizontal axis, and the reflectance on the vertical axis (Figure 2-20 provides a spectral signature for snow).

(2) *Important Reflectance Curves and Critical Spectral Regions*. While there are too many surface types to memorize all their spectral signatures, it is helpful to be familiar with the basic spectral characteristics of green vegetation, soil, and water. This in turn helps determine which regions of the spectrum are most important for distinguishing these surface types.

(3) *Spectral Reflectance of Green Vegetation.* Reflectance of green vegetation (Figure 2-21) is low in the visible portion of the spectrum owing to chlorophyll absorption, high in the near IR due to the cell structure of the plant, and lower again in the shortwave IR due to water in the cells. Within the visible portion of the spectrum, there is a local reflectance peak in the green (0.55 μm) between the blue (0.45 μm) and red (0.68 μm) chlorophyll absorption valleys (Samson, 2000; Lillesand and Kiefer, 1994).

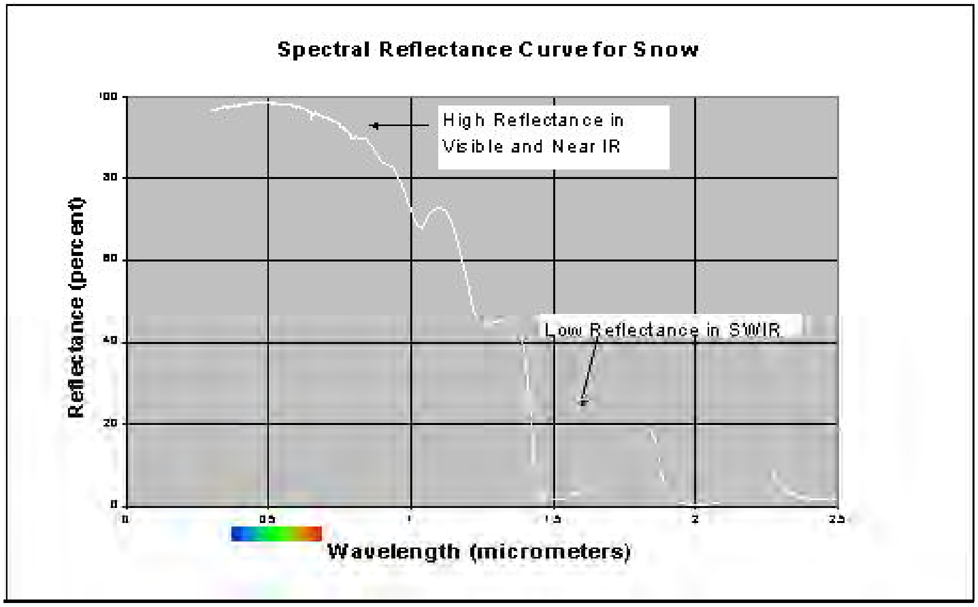


Figure 2-20. Spectral reflectance of snow. Graph developed for Prospect (2002 and 2003) using Aster Spectral Library (http://speclib.jpl.nasa.gov/) data

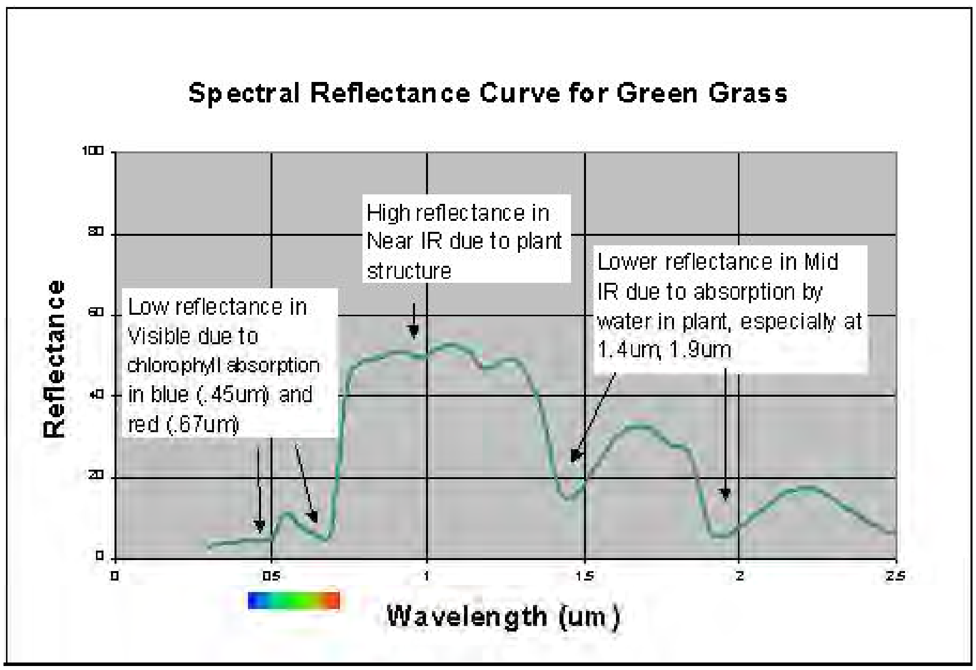


Figure 2-21. Spectral reflectance of healthy vegetation. Graph developed for Prospect (2002 and 2003) using Aster Spectral Library (http://speclib.jpl.nasa.gov/) data

(4) *Spectral Reflectance of Soil*. Soil reflectance (Figure 2-22) typically increases with wavelength in the visible portion of the spectrum and then stays relatively constant in the near-IR and shortwave IR, with some local dips due to water absorption at 1.4 and 1.9 µm and due to clay absorption at 1.4 and 2.2 µm (Lillesand and Kiefer, 1994).

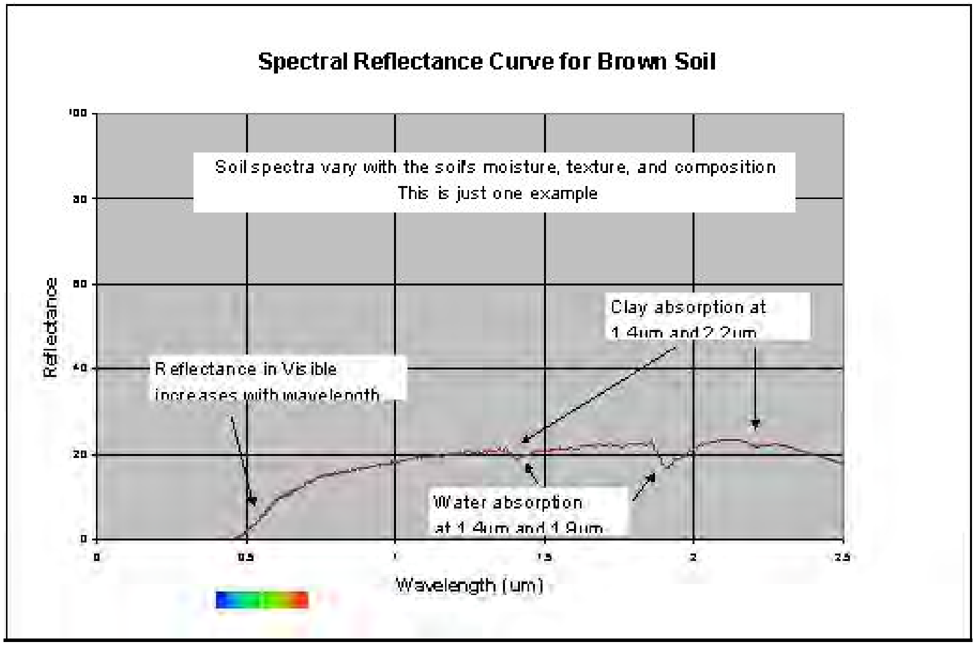


Figure 2-22. Spectral reflectance of one variety of soil. Graph developed for Prospect (2002 and 2003) using Aster Spectral Library (http://speclib.jpl.nasa.gov/) data

(5) *Spectral Reflectance of Water*. Spectral reflectance of clear water (Figure 2-23) is low in all portions of the spectrum. Reflectance increases in the visible portion when materials are suspended in the water (Lillesand and Kiefer, 1994).

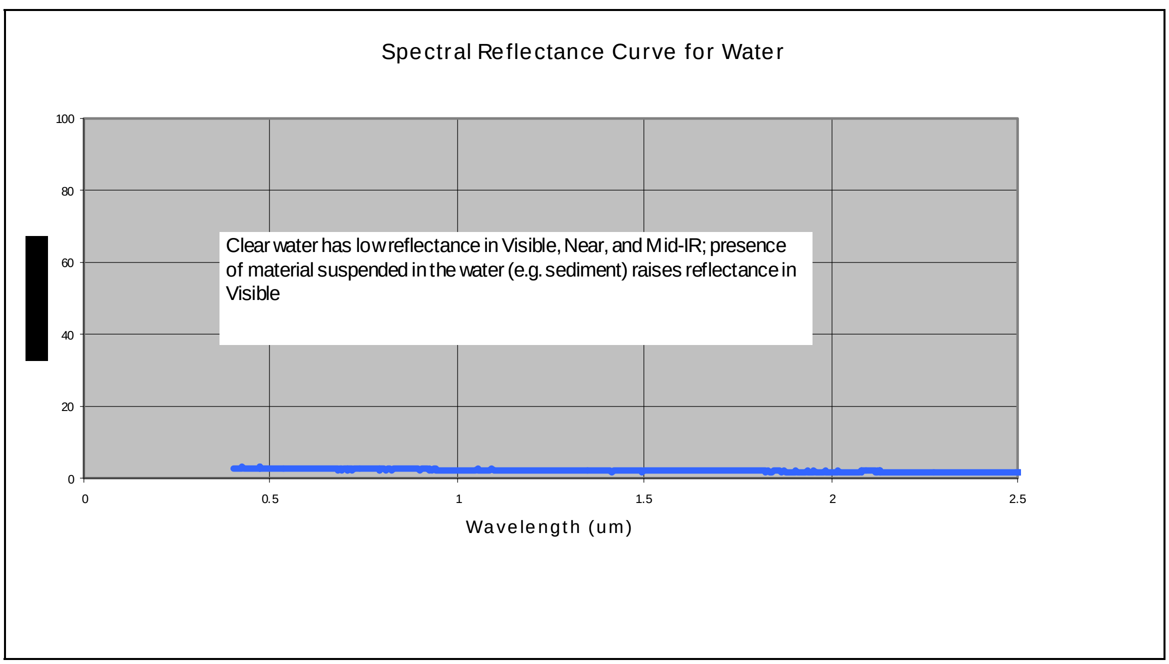


Figure 2-23. Spectral reflectance of water. Graph developed for Prospect (2002 and 2003) using Aster Spectral Library (http://speclib.jpl.nasa.gov/) data

(6) *Critical Spectral Regions*. The spectral regions that will be most useful in a remote sensing application depend on the spectral signatures of the surface features to be distinguished. The figure below (Figure 2-24) shows that the visible blue region is not very useful for separating vegetation, soil, and water surface types, since all three have similar reflectance, but visible red wavelengths separate soil and vegetation. In the near-IR (refers to 0.7 to 2.5 μm), all three types are distinct, with vegetation high, soil intermediate, and water low in reflectance. In the shortwave IR, water is distinctly low, while vegetation and soil exchange positions across the spectral region. When spectral signatures cross, the spectral regions on either side of the intersection are especially useful. For instance, green vegetation and soil signatures cross at about 0.7 μm, so the 0.6- (visible red) and 0.8-μm and larger wavelengths (near IR) regions are of particular interest in separating these types. In general, vegetation studies include near IR and visible red data, water vs. land distinction include near IR or SW IR. Water quality studies might include the visible portion of the spectrum to detect suspended materials.

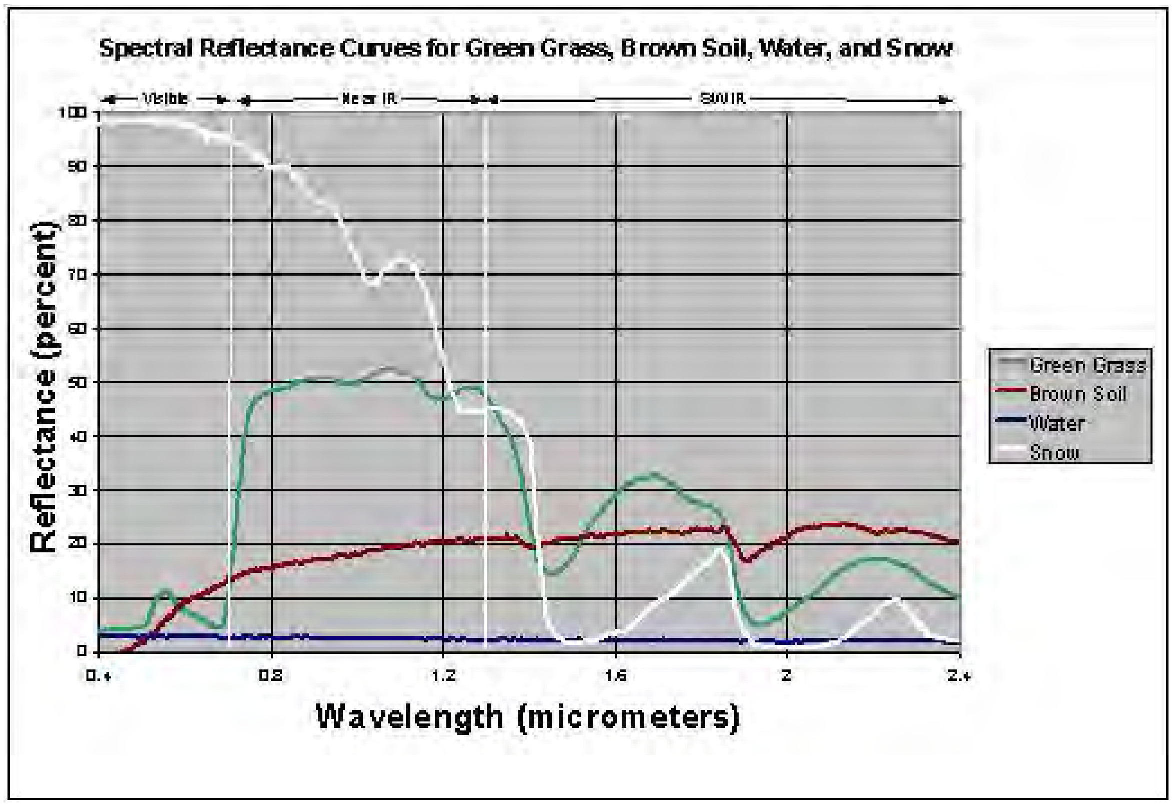


Figure 2-24. Spectral reflectance of grass, soil, water, and snow. Graph developed for Prospect (2002 and 2003) using Aster Spectral Library (http://speclib.jpl.nasa.gov/) data

(7) *Spectral Libraries*. As noted above, detailed spectral signatures of known materials are useful in determining whether and in what spectral regions surface features are distinct. Spectral reflectance curves for many materials (especially minerals) are available in existing reference archives (spectral libraries). Data in spectral libraries are gathered under controlled conditions, quality checked, and documented. Since these are re-

flectance curves, and reflectance is theoretically an unvarying property of a material, the spectra in the spectral libraries should match those of the same materials at other times or places.

(*a*) If data in spectral libraries are not appropriate, reflectance curves can be acquired using a spectrometer. The instrument is aimed at a known target and records the radiance reflected from the target over a fixed range of the spectrum (the 0.4- to 2.5-μm range is relatively common). The instrument must also measure the radiance coming in to the target, so that the reflected radiance can be divided by incoming radiance at each wavelength to determine spectral reflectance of the target. Given the time and expense of gathering spectra data, it is best to check spectral libraries first.

(*b*) Two major spectral libraries available on the internet (where spectra can be downloaded and processed locally if needed) include:

- US Geological Survey Digital Spectral Library (Clark et al. 1993)

http://speclab.cr.usgs.gov/spectral-lib.html
"Researchers at the Spectroscopy lab have measured the spectral reflectance of hundreds of materials in the lab and have compiled a spectral library. The libraries are used as references for material identification in remote sensing images."

- ASTER Spectral Library (Jet Propulsion Laboratory, 1999)

http://speclib.jpl.nasa.gov/
"Welcome to the ASTER spectral library, a compilation of almost 2000 spectra of natural and man made materials."

(*c*) The ASTER spectral library includes data from three other spectral libraries: the Johns Hopkins University (JHU) Spectral Library, the Jet Propulsion Laboratory (JPL) Spectral Library, and the United States Geological Survey (USGS—Reston) Spectral Library."

(8) *Real Life and Spectral Signatures*. Knowledge of spectral reflectance curves is useful if you are searching a remote sensing image for a particular material, or if you want to identify what material a particular pixel represents. Before comparing image data with spectral library reflectance curves, however, you must be aware of several things.

(*a*) Image data, which often measure radiance above the atmosphere, may have to be corrected for atmospheric effects and converted to reflectance.

(*b*) Spectral reflectance curves, which typically have hundreds or thousands of spectral bands, may have to be resampled to match the spectral bands of the remote sensing image (typically a few to a couple of hundred).

(*c*) There is spectral variance within a surface type that a single spectral library reflectance curve does not show. For instance, the Figure 2-25 below shows spectra for a number of different soil types. Before depending on small spectral distinctions to separate surface types, a note of caution is required: make sure that differences within a type do not drown out the differences between types.

(*d*) While spectral libraries have known targets that are "pure types," a pixel in a remote sensing image very often includes a mixture of pure types: along edges of types (e.g., water and land along a shoreline), or interspersed within a type (e.g., shadows in a tree canopy, or soil background behind an agricultural crop).

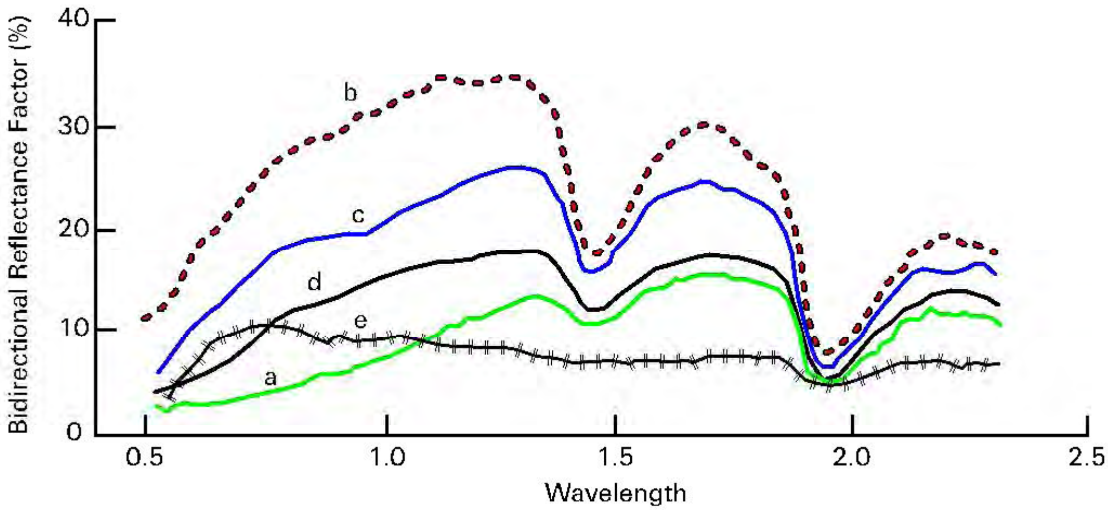


Figure 2-25. Reflectance spectra of five soil types: **A—s**oils having > 2% organic matter content (OMC) and fine texture; **B—** soils having < 2% OMC and low iron **content; C—**soils having < 2% OMC and medium iron content; **D—s**oils having > 2% OMC, and coarse texture; and E— soil having fine texture and high iron-oxide content (> 4%).

2-7 Component 4: Energy is Detected and Recorded by the Sensor.

Earlier paragraphs of this chapter explored the nature of emitted and reflected energy and the interactions that influence the resultant radiation as it traverses from source to target to sensor. This paragraph will examine the steps necessary to transfer radiation data from the satellite to the ground and the subsequent conversion of the data to a useable form for display on a computer.

a. Conversion of the Radiation to Data. Data collected at a sensor are converted from a continuous analog to a digital number. This is a necessary conversion, as electromagnetic waves arrive at the sensor as a continuous stream of radiation. The incoming radiation is sampled at regular time intervals and assigned a value (Figure 2-26). The value given to the data is based on the use of a 6-, 7-, 8-, 9-, or 10-bit binary computer coding scale; powers of 2 play an important role in this system. Using this coding allows a computer to store and display the data. The computer translates the sequence of binary numbers, given as ones and zeros, into a set of instructions with only two possible outcomes (1 or 0, meaning "on" or "off"). The binary scale that is chosen (i.e., 8 bit data) will depend on the level of brightness that the radiation exhibits. The brightness level is determined by measuring the voltage of the incoming energy. Below in Table 2-5 is a list of select bit integer binary scales and their corresponding number of brightness levels. The ranges are derived by exponentially raising the base of 2 by the number of bits.

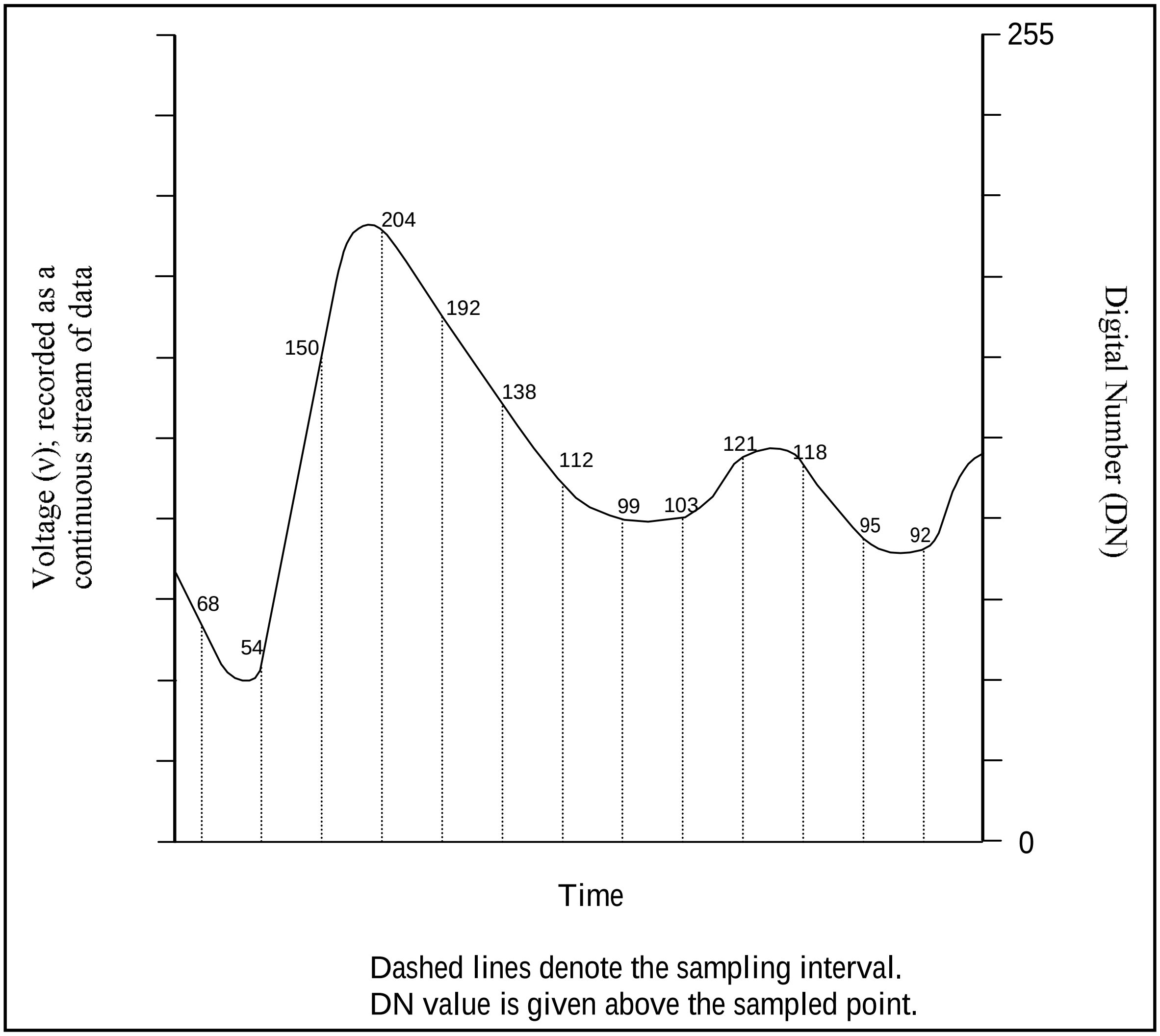


Figure 2-26. Diagram illustrates the digital sampling of continuous analog voltage data. The DN values above the curve represent the digital output values for that line segment.

Table 2-5
Digital number value ranges for various bit data

Number of bits	Exponent of 2	Digital Number (DN)	Value Range
6	2^6	64	0–63
8	2^8	256	0–255
10	2^{10}	1024	0–1023
16	2^{16}	65536	0–65535

b. Diversion on Data Type. Digital number values for raw remote sensing data are usually integers. Occasionally, data can be expressed as a decimal. The most popular code for representing real numbers (a number that contains a fraction, i.e., 0.5, which is one-half) is called the IEEE (Institute of Electrical and Electronics Engineers, pronounced I-triple-E) Floating-Point Standard. ASCII text (American Standard Code for Information Interchange; pronounced *ask-ee*) is another alternative computing value system. This system is used for text data. You may need to be aware of the type of data used in an image, particularly when determining the digital number in a pixel.

c. Transferring the Data from the Satellite to the Ground. The transfer of data stored in the sensor from the satellite to the user is similar to the transmission of more familiar signals, such as radio and television broadcasts and cellular phone conversations. Everything we see and hear, whether it is a TV program with audio or a satellite image, originates as a form of electromagnetic radiation. To transfer satellite data from the sensor to a location on the ground, the radiation is coded (described in Paragraph 2-7*a*) and attached to a signal. The signal is generally a high frequency electromagnetic wave that travels at the speed of light. The data are instantaneously transferred and detected with the use of an appropriate antenna and receiver.

d. Satellite Receiving Stations.

(1) Satellite receiving stations are positioned throughout the world. Each satellite program has its own fleet of receiving stations with a limited range from which it can pick up the satellite signal. For an example of locations and coverage of SPOT receiving stations go to
http://www.spotimage.fr/home/system/introexp/station/welcome.htm.

(2) Satellites can only transmit data when in range of a receiving station. When outside of a receiving range, satellites will store data until they fly within range of the next receiving station. Some satellite receiving stations are mobile and can be placed on airplanes for swift deployment. A mobile receiving station is extremely valuable for the immediate acquisition of data relating to an emergency situation (flooding, forest fire, military strikes).

e. Data is Prepared for User. Once transmitted the carrier signal is filtered from the data, which are decoded and recorded onto a high-density digital tape (HDDT) or a CD-ROM, and in some cases transferred via file transfer protocol (FTP). The data can then undergo geometric and radiometric preprocessing, generally by the vendor. The data are subsequently recorded onto tape or CD compatible for a computer.

f. Hardware and Software Requirements. The hardware and software needed for satellite image analysis will depend on the type of data to be processed. A number of free image processing software programs are available and can be downloaded from the internet. Some vendors provide a free trial or free tutorials. Highly sophisticated and powerful software packages are also available for purchase. These packages require robust hardware systems to sustain extended use. Software and hardware must be capable of managing the requirements of a variety of data formats and file sizes. A single satellite image file can be 300 MB prior to enhancement processing. Once processed and enhanced, the resulting data files will be large and will require storage for continued analysis. Because of the size of these files, software and hardware can be pushed to its limits. Regularly save and back up your data files as software and hardware pushed to its limits can crash, losing valuable information. Be sure to properly match your software requirements with appropriate hardware capabilities.

g. Turning Digital Data into Images.

(1) Satellite data can be displayed as an image on a computer monitor by an array of pixels, or picture elements, containing digital numbers. The composition of the image is simply a grid of continuous pixels, known as a raster image (Figure 2-27). The digital number (DN) of a pixel is the result of the spatial, spectral, and radiometric averaging of reflected/emitted radiation from a given area of ground cover (see below for information on spatial, spectral, and radiometric resolution). The DN of a pixel is therefore the average radiance of the surface area the pixel represents.

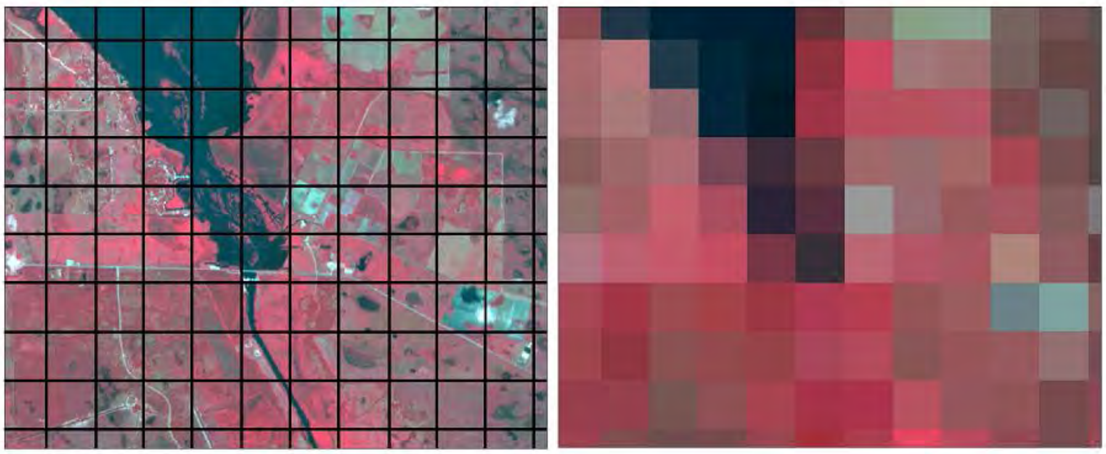


Figure 2-27. Figure illustrates the collection of raster data. Black grid (left) shows what area on the ground is covered by each pixel in the image (right). A sensor measures the average spectrum from each pixel, recording the photons coming in from that area. ASTER data of Lake Kissimmee, Florida, acquired 2001-08-18. Image developed for Prospect (2002 and 2003).

(2) The value given to the DN is based on the brightness value of the radiation (see explanation above and Figure 2-28). For most radiation, an 8-bit scale is used that corresponds to a value range of 0–255 (Table 2-4). This means that 256 levels of brightness (DN values are sometimes referred to as brightness values—B_v) can be displayed, each representing the intensity of the reflected/emitted radiation. On the image this translates to varying shades of grays. A pixel with a brightness value of zero ($B_v = 0$) will appear black; a pixel with a B_v of 255 will appear white (Figure 2-29). All brightness values in the range of $B_v = 1$ to 254 will appear as increasingly brighter shades of gray. In Figure 2-30, the dark regions represent water-dominated pixels, which have low reflectance/B_v, while the bright areas are developed land (agricultural and forested), which has high reflectance.

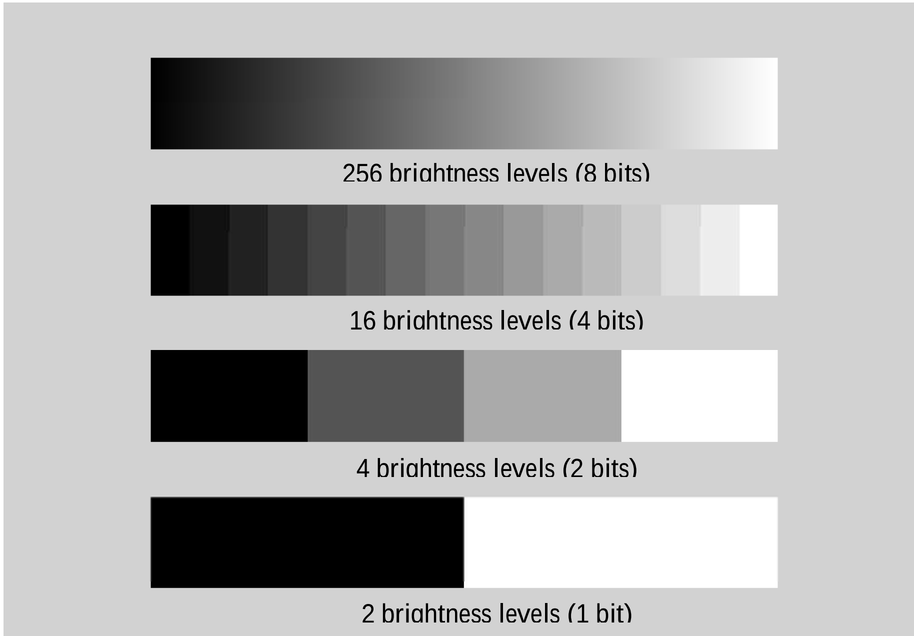
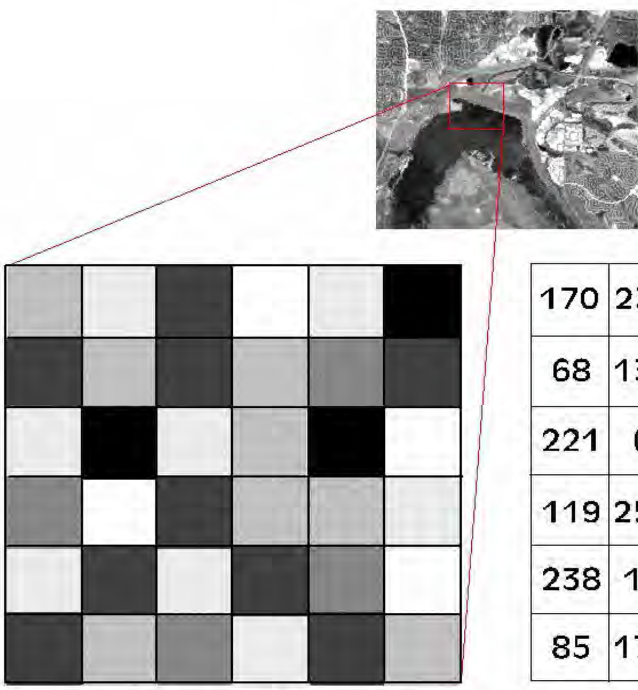


Figure 2-28. Brightness levels at different radiometric resolutions. Image developed for USACE Prospect #196 (2002).



170	238	85	255	221	0
68	136	17	170	119	68
221	0	238	136	0	255
119	255	85	170	136	238
238	17	221	68	119	255
85	170	119	221	17	138

Figure 2-29. Raster array and accompanying digital number (DN) values for a single band image. Dark pixels have low DN values while bright pixels have high values. Modified from Natural Resources Canada image http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter1/chapter1_7_e.html.

Figure 2-30. Landsat MSS band 5 data of San Francisco, California. The black pixels represent water; the various levels of gray to bright pixels represent different vegetation and ground cover types across the landscape. Image taken from http://sfbay.wr.usgs.gov/access/change_detect/Satellite_Images2.html.

h. Converting Digital Numbers to Radiance. Conversion of a digital number to its corresponding radiance is necessary when comparing images from different satellite sensors or from different times. Each satellite sensor has its own calibration parameter, which is based on the use of a linear equation that relates the minimum and maximum radiation brightness. Each spectrum band (see Paragraph 2-7*i*) also has its own radiation minimum and maximum.

(1) Information pertaining to the minimum and maximum brightness (L_{min} and L_{max} respectively) is usually found in the metadata (see Chapter 5). The equation for determining radiance from the digital number is:

$$L = (L_{max} - L_{min})/255 \times DN + L_{min} \tag{2-10}$$

where

L = radiance expressed in $Wm^{-2}\ sr^{-1}$
L_{min} = spectral radiance corresponding to the minimum digital number
L_{max} = spectral radiance corresponding to the maximum digital number
DN = digital number given a value based on the bit scale used.

(2) This conversion can also be used to enhance the visual appearance of an image by reassigning the DN values so they span the full gray scale range (see Paragraph 5-20).

i. Spectral Bands.

(1) Sensors collect wavelength data in bands. A number or a letter is typically assigned to a band. For instance, radiation that spans 0.45 to 0.52 μm is designated as band 1 for Landsat 7 data; in the microwave region radiation spanning 15 to 30 cm is termed the L-band. Not all bands are created equally. Landsat band 1 (B1) does not represent the same wavelengths as SPOT's B1.

(2) Band numbers are not the same as sensor numbers. For instance Landsat 4 *does not* refer to band 4. It instead refers to the fourth satellite sensor placed into orbit by the Landsat program. This can be confusing, as each satellite program has a fleet of satellites (in or out of commission at different times), and each satellite program will define bands differently. Two different satellites from the same program may even be collecting radiation at a slightly difference wavelength range for the same band (Table 2-6). It is, therefore, important to know which satellite program and which sensor collected the data.

Table 2-6
Landsat Satellites and Sensors
The following table lists Landsat satellites 1-7, and provides band information and pixel size. The band numbers for one sensor does not necessarily imply the same wavelength range. For example, notice that band 4 in Landsat 1-2 and 3 differ from the band 4 in Landsat 4-5 and Landsat 7. Source: http://landsat.gsfc.nasa.gov/guides/LANDSAT-7_dataset.html#8.

Satellite	Sensor	Band number	Band wavelengths	Pixel Size
Landsats 1-2	RBV	1)	0.45 to 0.57	80
		2)	0.58 to 0.68	80
		3)	0.70 to 0.83	80
	MSS	4)	0.5 to 0.6	79
		5)	0.6 to 0.7	79
		6)	0.7 to 0.8	79
		7)	0.8 to 1.1	79
Landsat 3	RBV	1)	0.45 to 0.52	40

Satellite	Sensor	Band number	Band wavelengths	Pixel Size
	MSS	4)	0.5 to 0.6	79
		5)	0.6 to 0.7	79
		6)	0.7 to 0.8	79
		7)	0.8 to 1.1	79
		8)	10.4 to 12.6	240
Landsat 4-5	MSS	4)	0.5 to 0.6	82
		5)	0.6 to 0.7	82
		6)	0.7 to 0.8	82
		7)	0.8 to 1.1	82
	TM	1)	0.45 to 0.52	30
		2)	0.52 to 0.60	30
		3)	0.63 to 0.69	30
		4)	0.76 to 0.90	30
		5)	1.55 to 1.75	30
		6)	10.4 to 12.5	120
		7)	2.08 to 2.35	30
Landsat 7	ETM	1)	0.45 to 0.52	30
		2)	0.52 to 0.60	30
		3)	0.63 to 0.69	30
		4)	0.76 to 0.90	30
		5)	1.55 to 1.75	30
		6)	10.4 to 12.5	150
		7)	2.08 to 2.35	30
	PAN	4)	0.50 to 0.90	15

j. Color in the Image. Computers are capable of imaging three primary colors: red, green, and blue (RGB). This is different from the color system used by printers, which uses magenta, cyan, yellow, and black. The color systems are unique because of differences in the nature of the application of the color. In the case of color on a computer monitor, the monitor is black and the color is projected (called additive color) onto the screen. Print processes require the application of color to paper. This is known as a subtractive process owing to the removal of color by other pigments. For example, when white light that contains all the visible wavelengths hits a poster with an image of a yellow flower, the yellow pigment will remove the blue and green and will reflect yellow. Hence, the process is termed subtractive. The different color systems (additive vs. subtractive) account for the dissimilarities in color between a computer image and the corresponding printed image.

(1) Similar to the gray scale, color can also be displayed as an 8-bit image with 256 levels of brightness. Dark pixels have low values and will appear black with some color, while bright pixels will contain high values and will contain 100% of the designated color. In Figure 2-31, the 7 bands of a Landsat image are separated to show the varying DNs for each band.

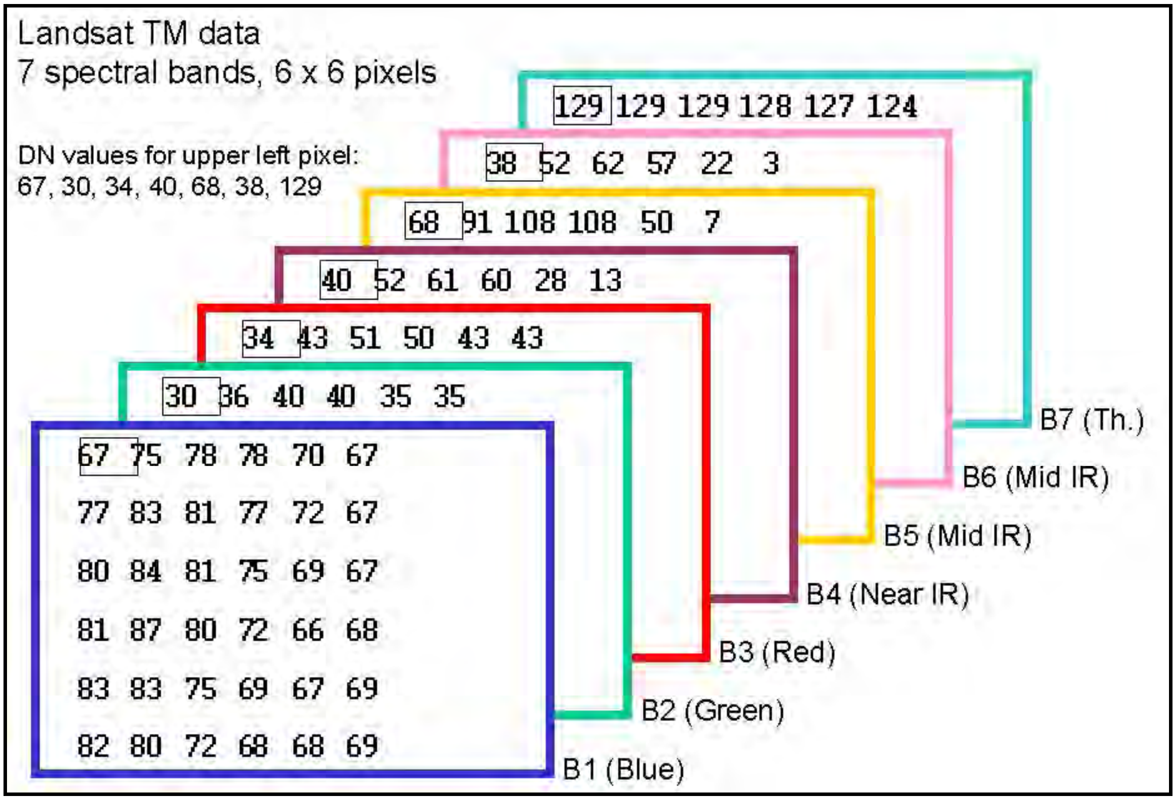
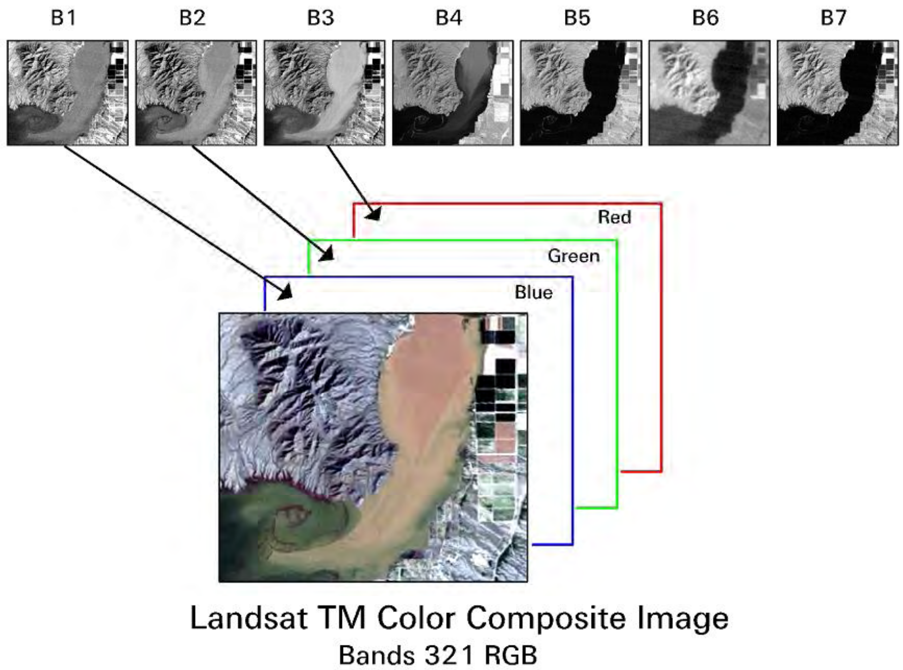


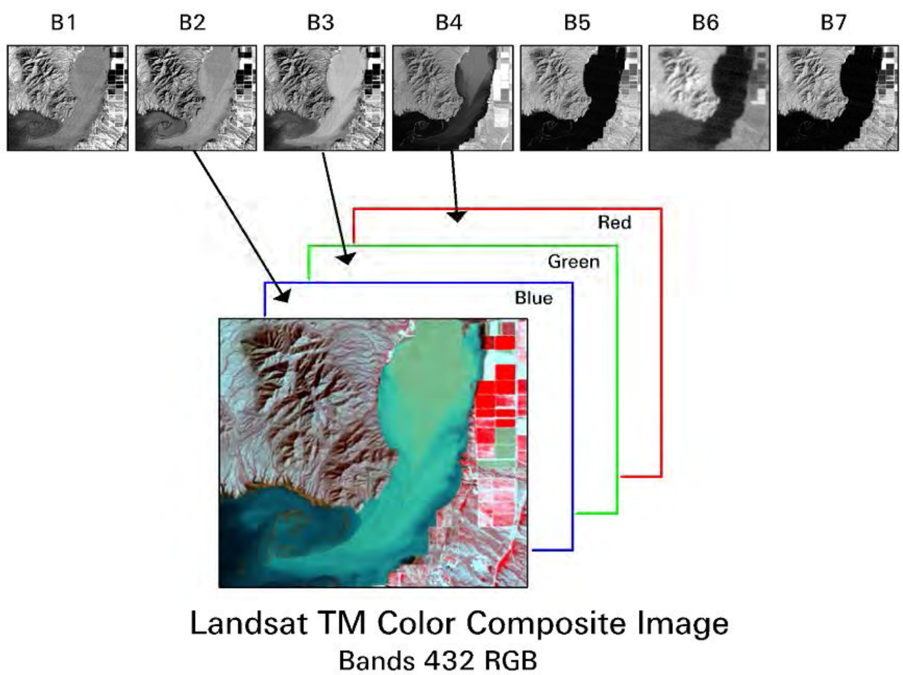
Figure 2-31. Individual DNs can be identified in each spectral band of an image. In this example the seven bands of a subset from a Landsat image are displayed. Image developed for Prospect (2002 and 2003).

(2) When displaying an image on a computer monitor, the software allows a user to assign a band to a particular color (this is termed as "loading the band"). Because there are merely three possible colors (red, green, and blue) only three bands of spectra can be displayed at a time. The possible band choices coupled with the three-color combinations creates a seemingly endless number of possible color display choices.

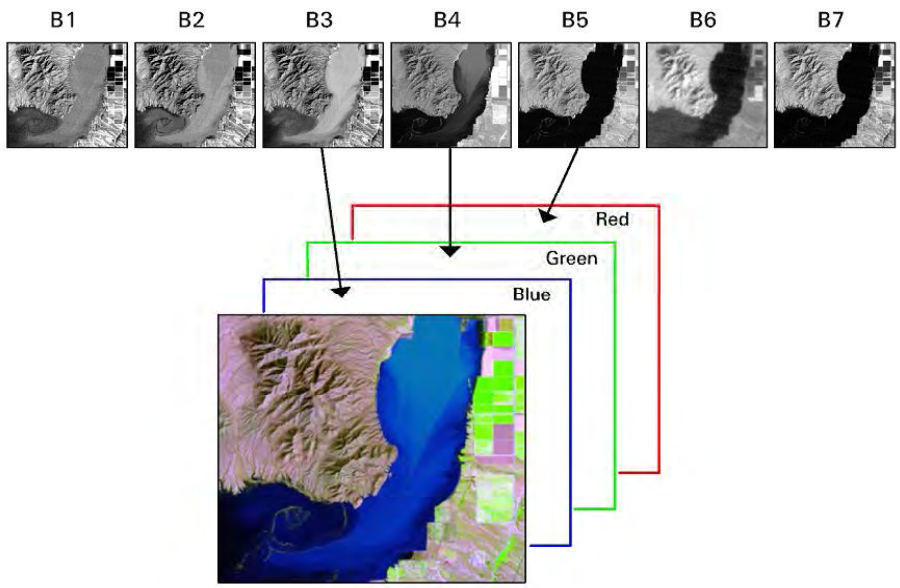
(3) The optimal band choice for display will depend of the spectral information needed (see Paragraph 2-6*b*(7)). The color you designate for each band is somewhat arbitrary, though preferences and standards do exist. For example, a typical color/band designation of red/green/blue in bands 3/2/1 of Landsat displays the imagery as true-color. These three bands are all in the visible part of the spectrum, and the imagery appears as we see it with our eyes (Figure 2-32a). In Figure 2-32b, band 4 (B4) is displayed in the red (called "red-gun" or "red-plane") layer of the bands 4/3/2, and vegetation in the agricultural fields appear red due to the infrared location on the spectrum. In Figure 2-32c, band 4 (B4) is displayed as green. Green is a logical choice for band 4 as it represents the wavelengths reflected by vegetation.



a. The true color image appears with these bands in the visible part of the spectrum.



b. Using the near infra-red (NIR) band (4) in the red gun, healthy vegetation appears red in the imagery.



Landsat TM Color Composite Image
Bands 543 RGB

c. Moving the NIR band into the green gun and adding band 5 to the red gun changes the vegetation to green.

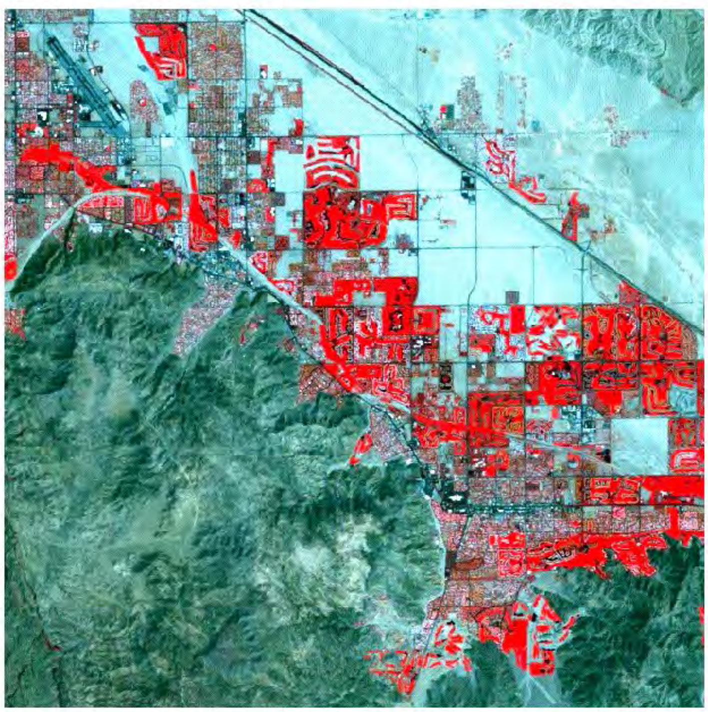
Figure 2-32. Three band combinations of Landsat imagery of 3/2/1, 4/3/2, and 5/4/3 in the RGB. Images developed for Prospect (2002 and 2003).

k. Interpreting the Image. When interpreting the brightness of a gray scale image (Figure 2-33), the brightness simply represents the amount of reflectance. For bright pixels the reflectance is high, while dark pixels represent areas of low reflectance. By example, in a gray scale display of Landsat 7 band 4, the brightest pixels represent areas where there is a high reflectance in the wavelength range of 0.76 to 0.90 μm. This can be interpreted to indicate the presence of healthy vegetation (lawns and golf courses).

(1) A color composite can be somewhat difficult to interpret owing to the mixing of color. Similar to gray scale, the bright regions have high reflectance, and dark areas have low reflectance. The interpretation becomes more difficult when we combine different bands of data to produce what is known as false-color composites (Figure 2-33).

(2) White and black are the end members of the band color mixing. White pixels in a color composite represent areas where reflectance is high in all three of the bands displayed. White is produced when 100% or each color (red, green, and blue) are mixed in equal proportions. Black pixels are areas where there is an absence of color due to the low DN or reflectance. The remaining color variations represent the mixing of three band DNs. A magenta pixel is one that contains equal portions of blue and red, while lacking green. Yellow pixels are those that are high in reflectance for the bands in the green and red planes. (Go to Appendix C for a paper model of the color cube/space.)

a



b

Figure 2-33. Landsat 7 image of southern California (a). Landsat TM band 4 image, the gray to bright white pixels represent the presence of healthy vegetation and urban development. (b). Landsat TM bands 4, 3, 2 (RGB) image, a false color composite, highlights vegetation in red. Images are taken from http://landsat.gsfc.nasa.gov/data/Browse/Comparisons/L7_BandComparison.html.

l. Data Resolution. A major consideration when choosing a sensor type is the definition of resolution capabilities. “Resolution” in remote sensing refers to the ability of a sensor to distinguish or resolve objects that are physically near or spectrally similar to other adjacent objects. The term high or fine resolution suggests that there is a large degree of distinction in the resolution. High resolution will allow a user to distinguish small, adjacent targets. Low or coarse resolution indicates a broader averaging of radiation over a larger area (on the ground or spectrally). Objects and their boundaries will be difficult to pinpoint in images with coarse resolution. The four types of resolution in remote sensing include spatial, spectral, radiometric, and temporal.

(1) *Spatial Resolution*.

(*a*) An increase in spatial resolution corresponds to an increase in the ability to resolve one feature physically from another. It is controlled by the geometry and power of the sensor system and is a function of sensor altitude, detector size, focal size, and system configuration.

(*b*) Spatial resolution is best described by the size of an image pixel. A pixel is a two-dimensional square-shaped picture element displayed on a computer. The dimensions on the ground (measured in meters or kilometers) projected in the instantaneous field of view (IFOV) will determine the ratio of the pixel size to ground coverage. As an example, for a SPOT image with 20- ×20-m pixels, one pixel in the digital image is equivalent to 20 m square on the ground. To gauge the resolution needed to discern an object, the spatial resolution should be half the size of the feature of interest. For example, if a project requires the discernment of individual tree, the spatial resolution should be a minimum of 15 m. If you need to know the percent of timber stands versus clearcuts, a resolution of 30 m will be sufficient.

Table 2-7
Minimum image resolution required for various sized objects.

Resolution (m)	Feature Object (m)
0.5	1.0
1.0	2.0
1.5	3.0
2.0	4.0
2.5	5.0
5.0	10.0
10.0	20.0
15.0	30.0
20.0	40.0
25.0	50.0

(2) *Spectral Resolution*. Spectral resolution is the size and number of wavelengths, intervals, or divisions of the spectrum that a system is able to detect. Fine spectral resolution generally means that it is possible to resolve a large number of similarly sized wavelengths, as well as to detect radiation from a variety of regions of the spectrum. A

coarse resolution refers to large groupings of wavelengths and tends to be limited in the frequency range.

(3) *Radiometric Resolution*. Radiometric resolution is a detector's ability to distinguish differences in the strength of emitted or reflected electromagnetic radiation. A high radiometric resolution allows for the distinction between subtle differences in signal strength.

(4) *Temporal Resolution*.

(*a*) Temporal resolution refers to the frequency of data collection. Data collected on different dates allows for a comparison of surface features through time. If a project requires an assessment of change, or change detection, it is important to know: 1) how many data sets already exist for the site; 2) how far back in time the data set ranges; and 3) how frequently the satellite returns to acquire the same location.

(*b*) Most satellite platforms will pass over the same spot at regular intervals that range from days to weeks, depending on their orbit and spatial resolution (see Chapter 3). A few examples of projects that require change detection are the growth of crops, deforestation, sediment accumulation in estuaries, and urban development.

(5) *Determine the Appropriate Resolution for the Project*. Increasing resolution tends to lead to more accurate and useful information; however, this is not true for every project. The downside to increased resolution is the need for increased storage space and more powerful hardware and software. High-resolution satellite imagery may not be the best choice when all that is needed is good quality aerial photographs. It is, therefore, important to determine the minimum resolution requirements needed to accomplish a given task from the outset. This may save both time and funds.

2-8 Aerial Photography. A traditional form of mapping and surface analysis by remote sensing is the use of aerial photographs. Low altitude aerial photographs have been in use since the Civil War, when cameras mounted on balloons surveyed battlefields. Today, they provide a vast amount of surface detail from a low to high altitude, vertical perspective. Because these photographs have been collected for a longer period of time than satellite images, they allow for greater temporal monitoring of spatial changes. Roads, buildings, farmlands, and lakes are easily identifiable and, with experience, surface terrain, rock bodies, and structural faults can be identified and mapped. In the field, photographs can aid in precisely locating target sites on a map.

a. Aerial photographs record objects in the visible and near infrared and come in a variety of types and scales. Photos are available in black and white, natural color, false color infrared, and low to high resolution.

b. Resolution in aerial photographs is defined as the resolvable difference between adjacent line segments. Large-scale aerial photographs maintain a fine resolution that allows users to isolate small objects such as individual trees. Photographs obtained at high altitudes produce a small-scale, which gives a broader view of surface features.

c. In addition to the actual print or digital image, aerial photographs typically include information pertaining to the photo acquisition. This information ideally includes the date, flight, exposure, origin/focus, scale, altitude, fiducial marks, and commissioner (Figure 2-34). If the scale is not documented on the photo, it can be determined by taking the ratio of the distance of two objects measured on the photo vs. the distance of the same two objects calculated form measurements taken from a map.

$$\text{Photo scale} = \text{photo distance/ground distance} = d/D \qquad (2\text{-}11)$$

Figure 2-34. Aerial photograph of a predominately agricultural area near Modesto, California. Notice the ancillary data located on the upper and right side margins. These data provide information regarding the location and acquisition of the photo.

d. The measurement is best taken from one end of the photo to the other, passing through the center (because error in the image increases away from the focus point). For precision, it is best to average a number of ratios from across the image.

e. Photos are interpreted by recognizing various elements in a photo by the distinction of tone, texture, size, shape, pattern, shadow, site, and association. For instance, airport landing strips can look like roads, but their large widths, multiple intersections at small angles, and the positioning of airport hangers and other buildings allow the interpreter to correctly identify these "roads" as a special use area.

f. Aerial-photos are shot in a sequence with 60% overlap; this creates a stereo view when two photos are viewed simultaneously. Stereoscopic viewing geometrically corrects photos by eliminating errors attributable to camera tilt and terrain relief. Images are most easily seen in stereo by viewing them through a stereoscope. With practice it is possible to see in stereo without the stereoscope. This view will produce a three-dimensional image, allowing you to see topographic relief and resistant vs. recessive rock types.

g. To maintain accuracy it is important to correlate objects seen in the image with the actual object in the field. This verification is known as ground truth. Without ground truth you may not be able to differentiate two similarly toned objects. For instance, two very different but recessive geologic units could be mistakenly grouped together. Ground truth will also establish the level of accuracy that can be attributed to the maps created based solely on photo interpretations.

h. For information on aerial photograph acquisition, see Chapter 4. Chapter 5 presents a discussion on the digital display and use of aerial photos in image processing.

2-9 Brief History of Remote Sensing. Remote sensing technologies have been built upon by the work of researchers from a variety of disciplines. One must look further than 100 years ago to understand the foundations of this technology. For a timeline history of the development of remote sensing see http://rst.gsfc.nasa.gov/Intro/Part2_8.html. The chronology shows that remote sensing has matured rapidly since the 1970s. This advancement has been driven by both the military and commercial sectors in an effort to effectively model and monitor Earth processes. For brevity, this overview focuses on camera use in remote sensing followed by the development of two NASA programs and France's SPOT system. To learn more about the development of remote sensing and details of other satellite programs see http://rst.gsfc.nasa.gov/Front/tofc.html.

a. The Camera. The concept of imaging the Earth's surface has its roots in the development of the camera, a black box housing light sensitive film. A small aperture allows light reflected from objects to travel into the black box. The light then "exposes" film, positioned in the interior, by activating a chemical emulsion on the film surface. After exposure, the film negative (bright and dark are reversed) can be used to produce a positive print or a visual image of a scene.

b. Aerial Photography. The idea of mounting a camera on platforms above the ground for a "birds-eye" view came about in the mid-1800s. In the 1800's there were few objects that flew or hovered above ground. During the US Civil War, cameras where mounted on balloons to survey battlefield sites. Later, pigeons carrying cameras were employed (http://www2.oneonta.edu/~baumanpr/ncge/rstf.htm), a platform with obvious disadvantages. The use of balloons and other platforms created geometric problems that were eventually solved by the development of a gyro-stabilized camera mounted on a rocket. This gyro-stabilizer was created by the German scientist Maul and was launched in 1912.

c. First Satellites. The world's first artificial satellite, Sputnik 1, was launched on 4 October 1957 by the Soviet Union. It was not until NASA's meteorological satellite TIROS –1 was launched that the first satellite images were produced (http://www.earth.nasa.gov/history/tiros/tiros1.html). Working on the same principles as the camera, satellite sensors collect reflected radiation in a range of spectra and store the data for eventual image processing (see above, this chapter).

d. NASA's First Weather Satellites. NASA's first satellite missions involved study of the Earth's weather patterns. TIROS (Television Infrared Operational Satellite) missions launched 10 experimental satellites in the early 1960's in an effort to prepare for a permanent weather bureau satellite system known as TOS (TIROS Operating System). TIROS-N (next generation) satellites currently monitor global weather and variations in the Earth's atmosphere. The goal of TIROS-N is to acquire high resolution, diurnal data that includes vertical profile measurements of temperature and moisture.

e. Landsat Program. The 1970's brought the introduction of the Landsat series with the launching of ERTS-1 (also known as Landsat 1) by NASA. The Landsat program was the first attempt to image whole earth resources, including terrestrial (land based) and marine resources. Images from the Landsat series allowed for detailed mapping of landmasses on a regional and continental scale.

(1) The Landsat imagery continues to provide a wide variety of information that is highly useful for identifying and monitoring resources, such as fresh water, timberland, and minerals. Landsat imagery is also used to assess hazards such as floods, droughts, forest fire, and pollution. Geographers have used Landsat images to map previously unknown mountain ranges in Antarctica and to map changes in coastlines in remote areas.

(2) A notable event in the history of the Landsat program was the addition of TM (Thematic Mapper) first carried by Landsat 4 (for a summary of Landsat satellites see http://geo.arc.nasa.gov/sge/landsat/lpsum.html). The Thematic Mapper provides a resolution as low as 30 m, a great improvement over the 70-m resolution of earlier sensors. The TM devise collects reflected radiation in the visible, infrared (IR), and thermal (IR) region of the spectrum.

(3) In the late 1970's, the regulation of Landsat was transferred from NASA to NOAA, and was briefly commercialized in the 1980s. The Landsat program is now oper-

ated by the USGS EROS Data Center (US Geological Survey Earth Resources Observation Systems; see http://landsat7.usgs.gov/index.html).

(4) As government sponsored programs have become increasingly commercialized and other countries develop their own remote sensors, NASA's focus has shifted from sensor development to data sharing. NASA's Data Acquisition Centers serves as a clearing-house for satellite data; these data can now be shared via the internet.

f. France's SPOT Satellite System. As a technology, remote sensing continues to advance globally with the introduction of satellite systems in other countries such as France, Japan, and India. France's SPOT (Satellite Pour l'Observation de la Terra) has provided reliable high-resolution (20 to 10 m resolution) image data since 1986.

(1) The SPOT 1, 2, and 3 offer both panchromatic data (P or PAN) and three bands of multispectral (XS) data. The panchromatic data span the visible spectrum without the blue (0.51-0.73 μm) and maintains a 10-m resolution. The multispectral data provide 20-m resolution, broken into three bands: Band 1 (Green) spans 0.50–0.59 μm, Band 2 (Red) spans 0.61–0.68 μm, and Band 3 (Near Infrared) spans 0.79–0.89 μm. SPOT 4 also supplies a 20-m resolution shortwave Infrared (mid IR) band (B4) covering 1.58 to 1.75 μm. SPOT 5, launched in spring 2002, provides color imagery, elevation models, and an impressive 2.5-m resolution. It houses scanners that collect panchromatic data at 5 m resolution and four band multispectral data at 10-m resolution (see Appendix D-"SPOT" file).

(2) SPOT 3 was decommissioned in 1996. SPOT 1, 2, 4, and 5 are operational at the time of this writing. For information on the SPOT satellites go to http://www.spotimage.fr/home/system/introsat/seltec/welcome.htm.

g. Future of Remote Sensing. The improved availability of satellite images coupled with the ease of image processing has lead to numerous and creative applications. Remote sensing has dramatically brought about changes in the methodology associated with studying earth processes on both regional and global scales. Advancements in sensor resolution, particularly spatial, spectral, and temporal resolution, broaden the possible applications of satellite data.

(1) Government agencies around the world are pushing to meet the demand for reliable and continuous satellite coverage. Continuous operation improves the temporal data needed to assess local and global change. Researchers are currently able to perform a 30-year temporal analysis using satellite images on critical areas around the globe. This time frame can be extended back with the incorporation of digital aerial photographs.

(2) Remote sensing has established itself as a powerful tool in the assessment and management of U.S. lands. The Army Corps of Engineers has already incorporated this technology into its nine business practice areas, demonstrating the tremendous value of remote sensing in civil works projects.